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Managing Saline Soils In the Red River Valley of the North

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INTRODUCTION

Research on saline soils of the Red River Valley of the North was conducted to determine the factors relating to (a) salt accumulation in this area and (b) reclamation and management of these salt-affected soils for agricultural production.

Saline soils (fig. 1) develop when dissolved salts in the soil increase the osmotic value of the soil solution and reduce the amount of water available to plants. Salts can also disturb plant metabolism and alter soil physical and chemical characteristics. In the moderately saline areas, barley and hay crops of alfalfa, clover, and bromegrass are grown. The highly saline areas are most often used for pasture or native grass hayland, although some are cultivated.

Approximately 400,000 acres are salt-affected in the Red River Valley in North Dakota. The Agricultural Research Service (ARS) began studies in 1955 on saline soils at the request of the Soil Conservation Service (SCS) and Soil Conservation Districts (SCD). Over 200,000 acres of saline land are located in Grand Forks County and about 200,000 acres of salt-affected soils are located north of Grand Forks in Walsh and Pembina Counties (fig. 2). Principal crops in Grand Forks County are small grains—wheat, barley, oats, and flax; row crops—potatoes, sugarbeets, corn, and sunflowers; and hay crops.

The Red River Valley in Canada also has considerable acreages of saline land (*21*).[2] Salt-affected soils in Minnesota—where the areas are small and scattered—total about 500,000 acres.[3] The development of salt-affected soils in the Red River Valley of North Dakota is distinctly associated with a high water table caused by (1) saline artesian water that leaks upward from the aquifer, (2) precipitation, and (3) poor drainage.

Early research goals were (a) to make chemical and physical characterizations of soils and waters, (b) to evaluate relationships of topography, water tables, and other factors to salt accumulation, and (c) to determine whether the soils could be improved by leaching through soil management techniques.

The first study on a saline and poorly drained area was a leaching experiment (*45*). This study was conducted to determine leaching effects and soil salinity relating to crop response but the experiment provided insufficient hydrologic information to evaluate the overall problem. Thus, additional studies were conducted to determine (a) soil and water characteristics and their relationship to salinity; (b) ground water regime, soils, salinity, and related topographic and relief factors; (c) effectiveness of shallow tile or plastic pipe drains; (d) effects of land grading and subsurface drainage on salinity in ridge (saline)-depression (nonsaline) microrelief areas; (f) soil water movement—particularly during the winter months; (g) effects of such soil management practices as fallowing, cropping, and residue managing; and (h) feasibility of pump drainage for water-table control and subsequent salinity control. Objectives and results of some of these studies will be discussed in the section dealing with management.

Information on stratigraphy and formations underlying the saline area was needed, but few data were

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[2]Italic numbers in parentheses refer to Literature Cited, p. 44.

[3]Private communication from H. M. Majors, Minnesota State Conservationist, U.S. Soil Conservation Service.

available. Until recently North Dakota had no laws requiring well drillers to file water-well logs with a state agency as is required for oil- and gas-well logs (bedrock formations). In Grand Forks County, only limited geological information is available from the oil drilling industry. The U.S. and State Geological Surveys do most of their drilling as exploration for good quality ground water supplies, and most of this drilling has been done for municipalities. Although recent countywide ground water resource studies have contributed some information on geology (*24*) and ground water resources (*27, 28, 29*), more data is needed on formations underlying the saline area.

Geological information available (*2, 30, 31, 50*)

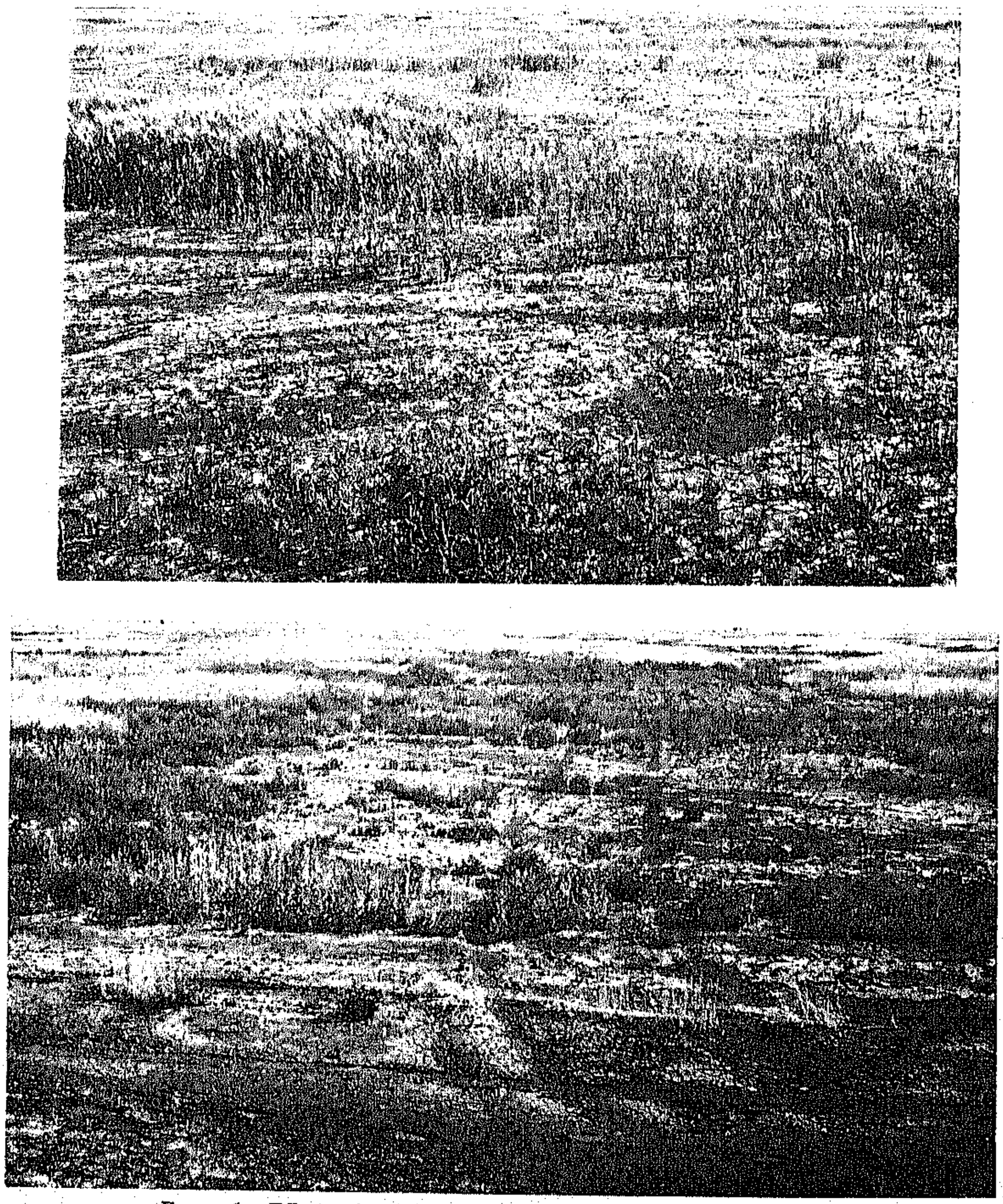


FIGURE 1.—Effects of salinity on crops, barley (*top*), wheat (*bottom*).

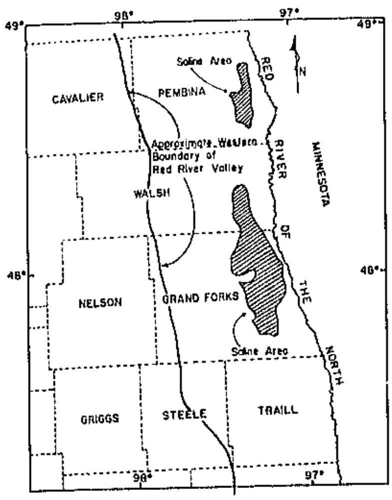


FIGURE 2.—Saline soils in northeastern North Dakota (from Soil Conservation Service and North Dakota State University soil survey maps).

suggested that many shallow (domestic) artesian wells end in sand and gravel lenses located in glacial drift. Deeper artesian wells ended in the Dakota Sandstone or in deeper formations, and upward leakage from deeper artesian formations was taking place into sand and gravel lenses in the glacial till. Because exploratory drilling is costly, an effort was made to delineate vertically and horizontally some of the sand and gravel lenses and geologic formations by less costly methods. The objective of these aspects of the study was to consider pumping or some other means of relieving the artesian head (*11*).

The purpose of this report is to summarize 17 years of research results on characteristics of and management techniques for salt-affected soils in the Red River Valley of the North, particularly in North Dakota. Further, these data may be applied to improve agricultural production in this extensive area.

INVESTIGATING SALINITY AND DRAINAGE

CLIMATE

Climate of the area (table 11 in app.) is the continental type—cold snowy winters, warm summer days, and cool summer nights—with a variety of weather systems in summer and winter.

The long-term average annual precipitation at Grand Forks is 19.8 inches. Of this amount more than three-fourths falls during the growing season, April through September. The average monthly totals of 3.48 inches in June, 2.50 inches in May, 2.85 inches in July, and 2.80 inches in August make an ideal distribution for the growing season. Precipitation events of 1 inch or more occur on an average of 3 or 4 days a year. Rainfall intensities of 1.05 inches in 1 hour, 1.55 inches in 6 hours, and 1.90 inches in 24 hours can be expected once every 2 years. The annual snowfall totals 34.5 inches, with the 4 months—November through February—each averaging slightly more than 6 inches per month. Total average snow depth during the winter is usually less than 10 inches.

The mean temperature for the winter months of December, January, and February is 7.7° F and the average temperature for the 3 summer months—June, July and August—is 66.3°.

Average wind movement for the year is about 9.5 mi/h. The prevailing direction is northwest except for the summer months when the prevailing direction is southeast. The area receives about 60 percent of the possible sunshine ranging from 45 percent in the winter to over 70 percent in the summer.

The average date of the last killing frost in the spring is May 15 and the average date of the first killing frost in the fall is September 24, hence, the frost-free growing season averages 131 days per year.

GEOLOGY

Warren Upham (*50*), one of the early writers to make a comprehensive study of the Red River Valley area, mapped the basin of old glacial Lake Agassiz and named most of its geomorphological features. Carbon-14 dating techniques indicate that the most recent ice sheet covering the area was ablated between 11,650 and 10,960 years ago (*31*). Thus, in geologic time, the Red River Valley is young.

Known geologic formations present in Grand Forks County are shown by two east-west cross sections (fig. 3). The stratigraphic sequence of formations from the ground surface downward is (a) alluvium (glacial-lacustrine sediments) of recent age, (b) glacial drift of Pleistocene age, (c) shales and sandstones of Cretaceous age, (d) limestones, shales, and sandstones of Ordovician age, and (e) weathered and unweathered igneous and metamorphic rocks of Precambrian age (*24*). Precambrian schists and granites occur at depths of 300 to 600 feet in eastern Grand Forks County. The upper part of this formation of vari-

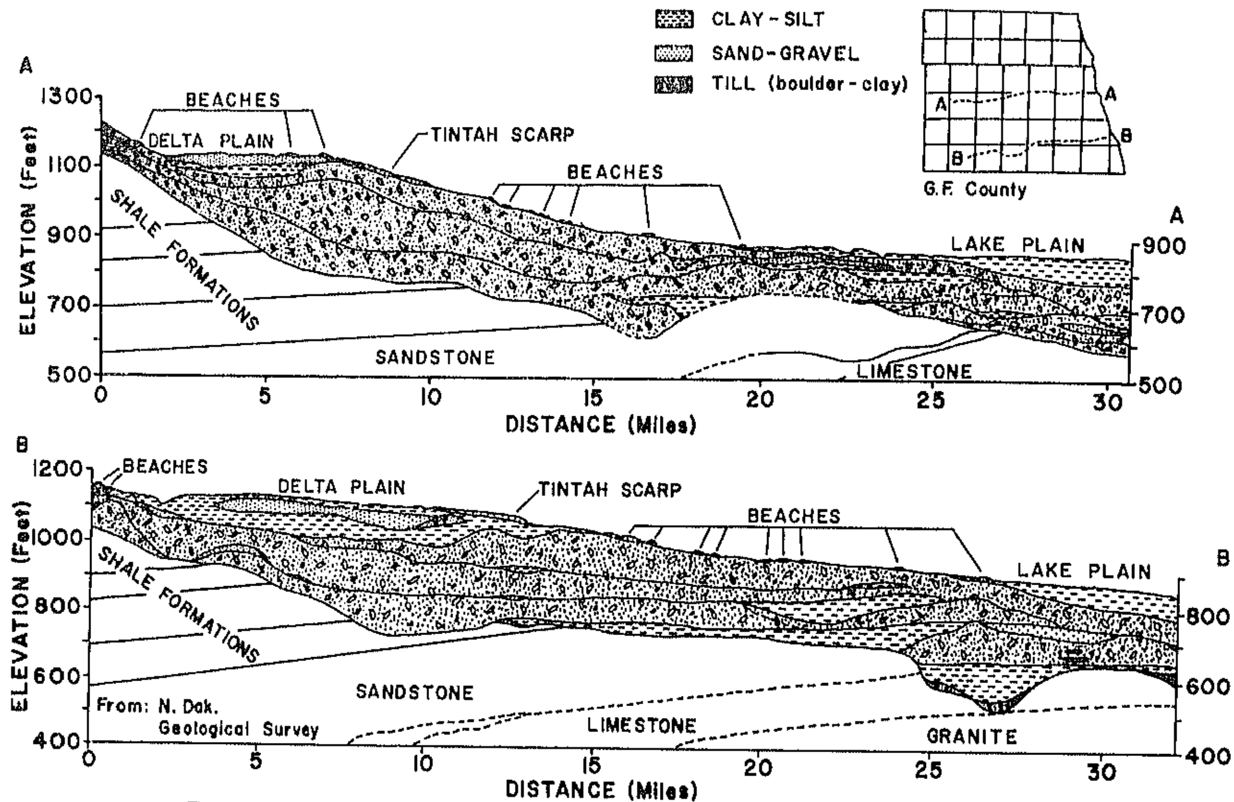


FIGURE 3.—Geological profiles in central and southern Grand Forks County (*25*).

colored clay is generally called weathered granite (*2*). There are no rocks present representing the time between the Precambrian to Cretaceous period, thus, in most of the area, Cretaceous rocks overlie the Precambrian rocks. During this long interval of exposure and erosion, indicated by the weathered and eroded Precambrian rocks, the Williston Basin, in the western part of North Dakota, was slowly sinking and filling with sediments. The Red River Valley is the eastern edge of the Basin (*14*).

Before the glacier advanced, sands, silts, clays, and limestones were deposited during submergence by seas, but these sediments were also eroded during periods when the area rose above the seas. As a result of the shape of the Williston Basin, subsequent deposited formations took on that same shape and, thus, bedrock formations slope upward from the west into the Red River Valley (*13*). The Ordovician system consists mostly of limestone and some shales and sandstones. This geologic system is thinner on the eastern side because of glacial erosion; the Ordovician system apparently has an aquifer, but the water is probably of poorer quality than that in the Dakota Sandstone (*29*).

Cretaceous rocks, over 600 feet thick in western Grand Forks County, are often found less than 100 feet below the ground surface but have been extensively eroded by glaciers in eastern Grand Forks County. The shale formations of Pierre, Niobrara, Carlile, and Greenhorn overlie the sandstone and shale formations in the Dakota Group (usually called Dakota Sandstone). Artesian flow from the Dakota Sandstone aquifer usually comes from the Fall River and Lakota formations although it may also occur from the Newcastle formation. The Dakota Group of Cretaceous age has an average thickness of about 100 feet in Grand Forks County, but it is several hundred feet thick in some areas of the western half of the County. This sandstone formation was completely removed by glaciation near the Red River, and its top can be less than 100 feet below ground surface in the saline area (*29, 30*). The basal Dakota usually consists of fine to coarse white sand, but in some places it has inter-bedded silt, sand, and gray clay. This group conformably overlies the Ordovician limestones and in turn is conformably overlain by the glacial deposits in the central and east and by the Colorado Group shales in western North Dakota (*29*).

Several ice sheets covered Grand Forks County during Pleistocene time. Each ice sheet probably left

deposits of drift with each successive glacier removing and redistributing part of the deposits of its predecessor. Each drift is a mixture of sand, gravel, and boulders in a silt-clay matrix that is usually quite compact as a result of tremendous pressures exerted by the tons of ice overlying the till material. Thickness of the glacial drift sheet varies from 50 to 350 feet. Occasionally, isolated sand and gravel or silt and clay lenses or layers occur between the till layers (*30*).

The final ice sheet covering the area left the topography with a regional slope to the northeast. As the sheet retreated to the north, it blocked the drainage and formed a large proglacial lake (Lake Agassiz). The lake covered a large area of eastern North Dakota and western Minnesota in the United States and southern Manitoba in Canada. Numerous stages of Lake Agassiz occurred as evidenced by a minor ridge-depression microrelief and the several beaches lying on the lake-deposited silts and clays near the axial portion of the basin; other evidence includes the beaches lying on the wave-planed till and the deltaic deposits beyond the Basin axis (*31*).

The lake sediments, which lie adjacent to the Red River, are of two main types according to Laird (*31*). The sediments lying on the till are a bedded, laminated clay. Upper lake sediments, those at and just below the ground surface, are brown silty clay and silt. The silt does not extend as far as does the laminated clay and is in an unconformable relationship with the underlying clay.

The Elk Valley Delta in western Grand Forks County consists of silts and sands, has an average thickness of 50 feet, and lies directly on the till.

The beach sediments are predominantly gravel with some sand. They unconformably overlie the planed till, deltas, and silts and clays. Beaches were formed during intermittent periods of a declining lake water level. All the beaches are discontinuous and most are multiple (*50*).

METHODS AND PROCEDURES

An area west of Grand Forks, N. Dak.—about 200 square miles in size including some of the saline and nonsaline areas—was selected for expanded ground water studies. To study artesian pressures and ground water flow, a grid network of 15-foot shallow observation wells and 20-foot piezometers,[4] plus batteries of piezometers, at various locations and depths (usually 20-, 40-, and 60-feet) were installed. The dashed line in figure 4 indicates the study area. Some additional studies were conducted in portions of the large saline area to the north of the 200-square mile study area.

Observation wells and piezometers were installed on a 2-mile grid pattern usually near a section corner or an out-of-the-way property boundary. The well sites had both 4- and ⅜-inch diameter pipes. Installations of the 4-inch wells were made by drilling, thus permitting observation and retention of soil samples and soil cores (*35*). The well casings were coal-tar-impregnated fiber pipe—a chemically inert material. The ⅜-inch diameter piezometers and wells were usually installed by jetting (*7, 34*). During jetting, the soils and formations encountered were analyzed by "feel" or "response" of the pipe and by examination of the materials in the jetting effluent that came to the ground surface.

The jetting technique was used in much of the shallow formation exploratory work, but it was slow and depth of penetration was limited. The penetration depth of ⅜-inch piezometers was limited to about 100 feet. Speed of jetting was limited by boulders and rocks that often stopped the operation and necessitated pipe removal and relocation to a new site.

The electrical resistivity method (*22*) for locating geological strata was used and compared to logs obtained by jetting and sampling (*7*). This resistance method consists essentially of measuring the resistance to electrical current flow by subsurface formations; it is an inexpensive and rapid manner to obtain geologic information.

Specific yields were evaluated from 3- by 3-inch soil cores that were saturated for 64 hours, then drained for 30 hours at 70-cm water tension.

Soil and water chemical analyses were performed as outlined in U.S. Department of Agriculture Handbook No. 60 (*38*). Soil salinity was evaluated from saturated soil extracts. Water samples, obtained through piezometers, indicated ground water chemistry at the terminal point of the particular piezometer whereas water samples from observation wells gave an integrated value for the saturated soil depth of the well.

[4]A small diameter pipe driven or jetted into the soil, open at the top and bottom, that measures the hydraulic pressure at the bottom end of the pipe in the soil.

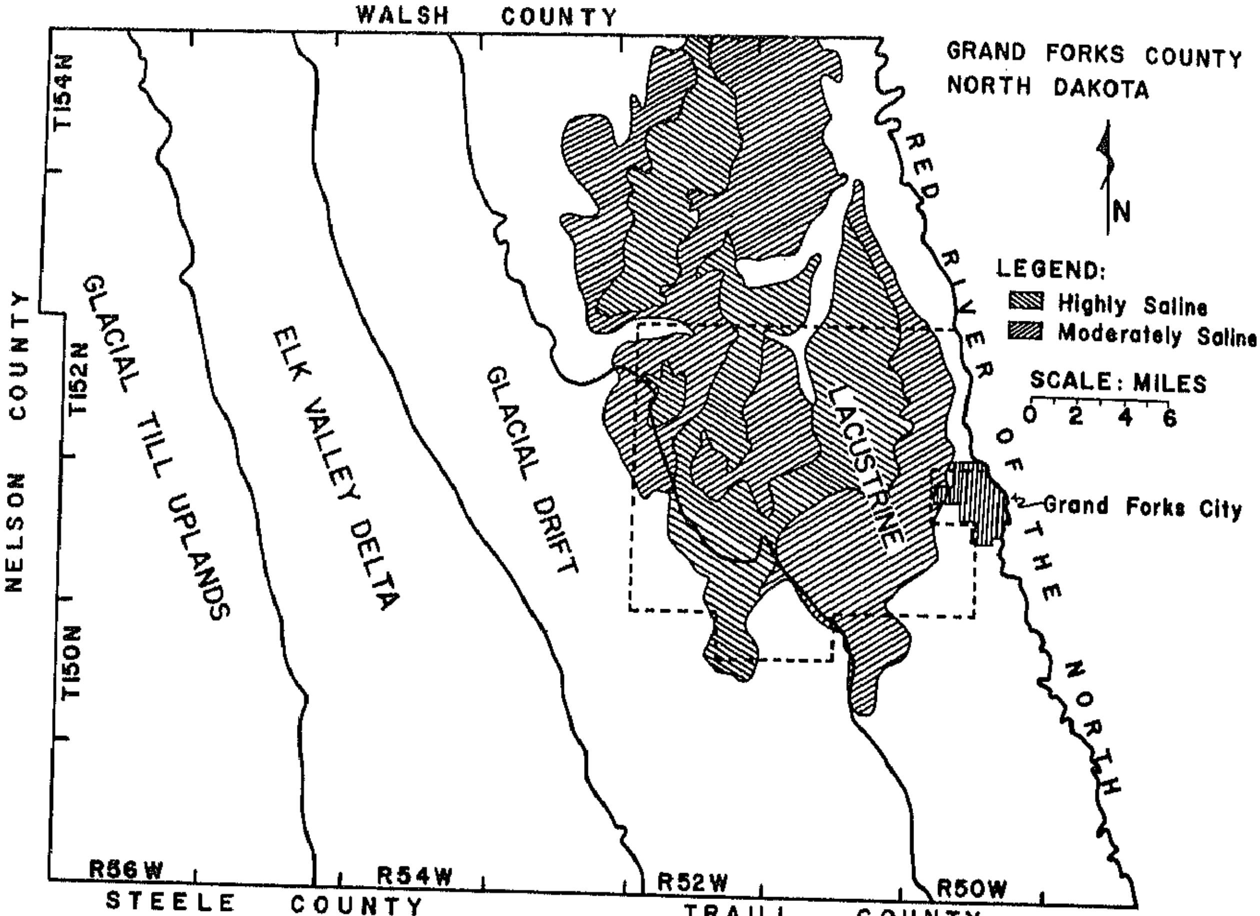


FIGURE 4.—Surface physiographic areas, saline soils and the main hydrologic study area (delineated by dotted line) in Grand Forks County, N. Dak.

TOPOGRAPHY, RELIEF, AND DRAINAGE

The Red River Valley is an old lake bed of ancient glacial Lake Agassiz, named after the famous Swiss geologist (*50*). The Valley slopes northward with mean sea level elevations from 905 feet at Fargo and 830 feet at Grand Forks to 790 feet at Pembina, giving an average slope of about 0.75 ft/mi. The Red River of the North, a winding stream, has a fall of 0.5 ft/mi and flows north into Canada. The general slope of the Valley in North Dakota is downward to the northeast (*3*).

Within North Dakota, the Red River Valley is 10 miles wide at the southern end and 30 miles wide at the Canadian boundary. The Red River forms the boundary between North Dakota and Minnesota and divides the Valley. It also acts as the primary drainage channel for the Valley plus a portion of the uplands on each side of the Valley and is part of the Hudson Bay drainage system.

The ground surface topography of east central Grand Forks County (fig. 5) slopes upward about 2.5 ft/mi from Grand Forks to 12 miles west of Grand Forks. From the point 12 miles west of Grand Forks

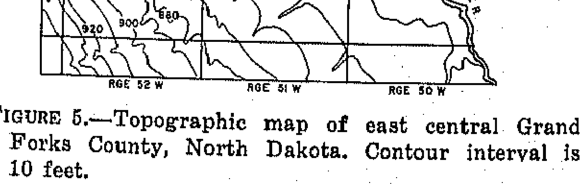


FIGURE 5.—Topographic map of east central Grand Forks County, North Dakota. Contour interval is 10 feet.

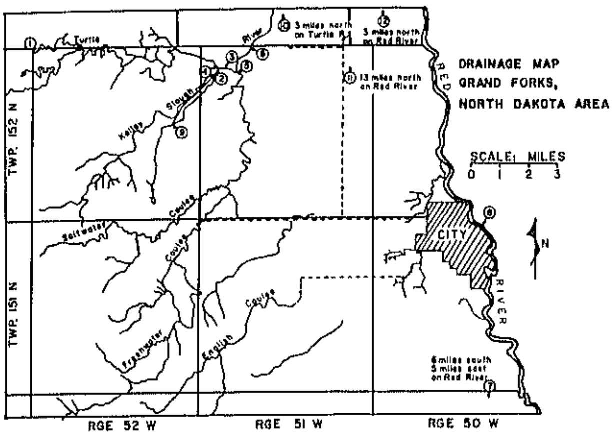


FIGURE 6.—Natural and artificial surface drains in east central Grand Forks County.

to the edge of the Valley—about 30 miles west of Grand Forks—the slope gradually increases to 10 to 15 ft/mi.

About 10 ancient beaches lie between the western edge of the Valley and 6 miles west of Grand Forks; axes are northwest-southeast. Beaches vary in height from several inches to about 20 feet with gentle sideslopes and are usually from ½ to 3 miles apart.

The Elk Valley Delta is located on the western edge of the Valley. The deposit materials, high in silt, presumably were transported into the glacial Lake Agassiz from the west by streams that were fed by large amounts of pluvial runoff (*24*).

The saline areas in Grand Forks County are poorly drained (fig. 6). Portions of the area are so nearly level that flow of water is often governed more by artificial than by natural barriers.

Streams of the area flow in a general northeasterly direction. All except the Red River have been developed since the Lake receded and are intermittent. The largest stream, apart from the Red River, is the Turtle River, which has a gradient of about 6.5 ft/mi. Water sources along the intermittent streams are springs, seeps, and flowing artesian wells.

A peculiar ridge-depression microrelief usually existing on the Valley floor is present in saline and nonsaline areas. The ridge crests are from several inches to several feet higher than adjacent depressions and range from 75 to 200 feet apart. Their axes usually parallel the ground surface contours, but they often are curved and sometimes intersect (fig. 7).

Colton (*17*) believed that the ridges formed when the fluctuating lake level fell, and the soft lake mud was squeezed upward into cracks in thick lake ice. Horberg (*25*) theorized that the lineations represent an unusual type of permafrost-patterned ground or tundra sheet. Clayton and others (*16*) believed that the ridges and troughs were caused by wind driven ice chunks being dragged in shallow water on the lake floor.

SOILS

The work of Jensen and Neil (*26*) is the earliest recorded description of saline soils in Grand Forks County and the Red River Valley. Four major soil physiographic areas occur in the County (fig. 4). Progressing westward are the lake-laid silts and clays in the east along the Red River, then glacial till, deltaic silts, and glacial till uplands. The two principal soil parent materials in the saline area are the lacustrine sediments and the glacial drift materials (*43, 46*). Other less important physiographic soil units are the ancient beach sands and gravels and low-lying, poorly drained, fine-textured, slough areas.

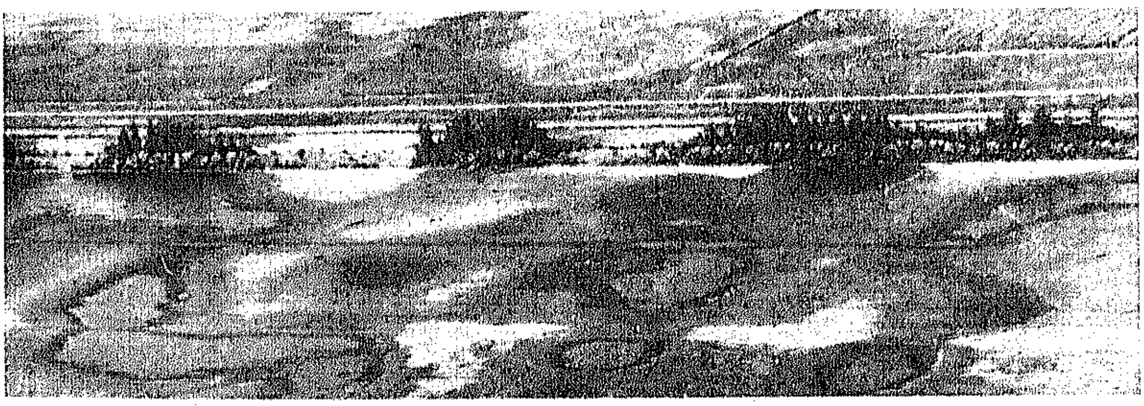


FIGURE 7.—Sawtooth shelterbelt showing ridge-depression and saline areas.

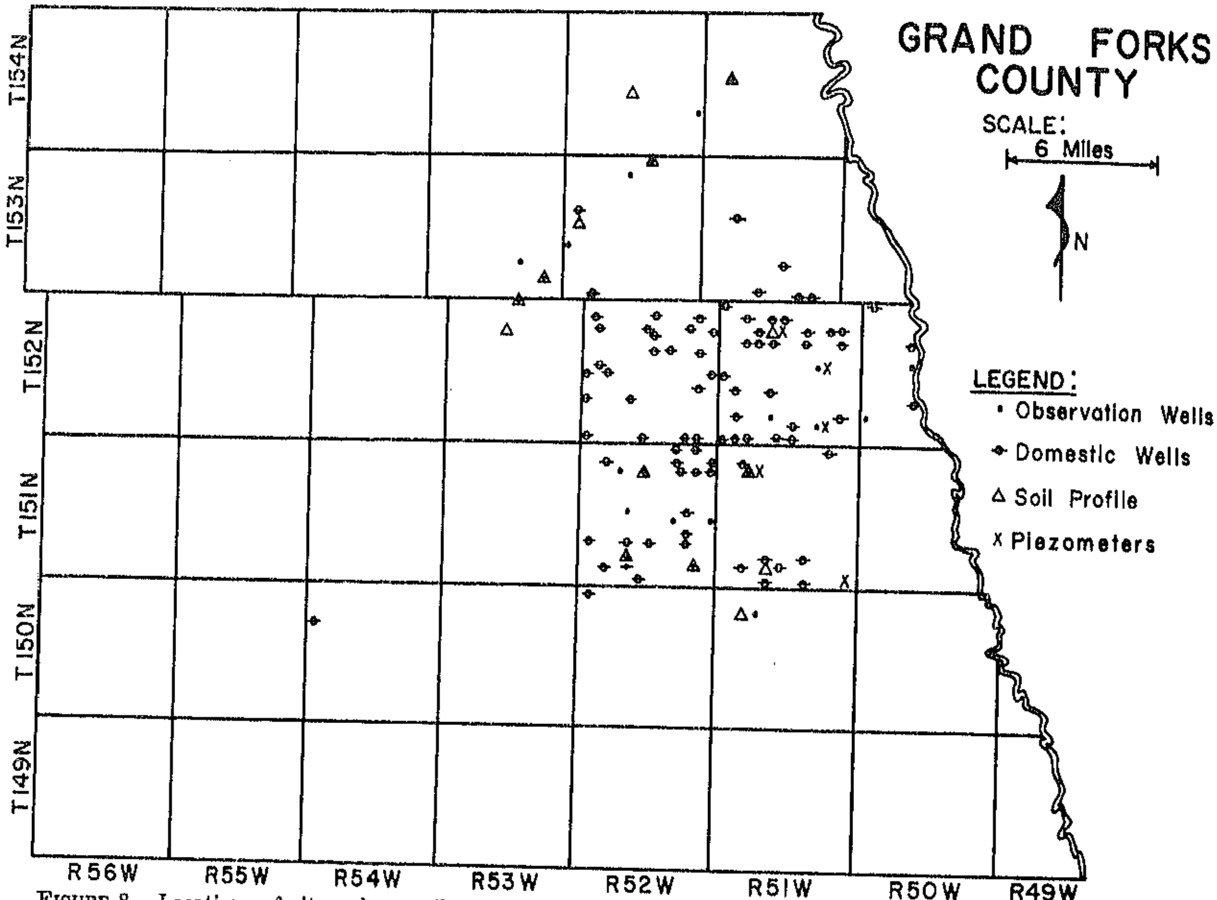


FIGURE 8.—Locations of sites where soil and ground water samplings were made for laboratory analyses.

Glyndon and Bearden are principal soil series located on the deep lacustrine sediments; Grimstad, Hamerly, Sletten, and other soils are present in the area where glacial drift is near or at the surface.[5]

Soil chemical data of several representative profiles are given in tables 12 and 13, in appendix. Soil profile locations are shown in figure 8. The saline lacustrine soils have a distinctly different chemistry, primarily in boron and magnesium contents, than the saline glacial till soils. Magnesium is low and boron is high in the glacial till areas. However, magnesium to calcium ratios are high in the lacustrine soils because the magnesium is high in these soils.

Saturation percentages (SP)[6] are higher in the lacustrine and till soils, compared to the beach soils —a reflection of finer textures. Electrical conductivities (EC) of saturation extracts are variable but usually high, depending upon the area and microrelief position. A comparison of profiles 8 and 16 (table 12 in app.), which were adjacent to each other, indicates the effect of microrelief position. Profile 8, taken on the ridge, is saline; whereas profile 16, taken in the depression, is nonsaline.

Because exchangeable-sodium-percentage (ESP) exceeded 15 and EC was greater than 4 mmhos/cm (millimhos per centimeter) the glacial till soils (near the surface) are classified as saline-sodic. An empirical relationship exists between the ESP of the soil and the calculated sodium-adsorption-ratio (SAR) of the soil solution. The lacustrine soils are more saline than till soils and dominant anions are sulfates and chorides. The pH of saturated soils usually ranges from 7.0 to 8.3.

The soils north of the Turtle River (north of the hydrologic study area—fig. 4), described in table 13, in appendix, have a slightly different chemistry than the soils south of the Turtle River (in the primary study area) as shown in table 12. Most soils north of

[5]Soil series names were obtained in 1960 from the Soil Conservation Service, USDA; however, soil series names are subject to change.

[6]See USDA Agriculture Handbook No. 60 for definitions and formulas.

the Turtle River are relatively low in adsorbed or exchangeable sodium and salinity is variable; as salinity increases the SAR increases.

The cation-exchange-capacity (CEC), usually higher in the surface horizons, is associated with the high organic matter in the surface soils.

Mechanical analysis of several soils is given in table 14, in appendix. In lacustrine soils, silt was the major constituent followed by clay with sand content being low. Silt usually accounts for more than 60 percent and sometimes approaches 90 percent of the soil minerals. Clay ranges from 10 to 40 percent; sand is usually less than 5 percent.

Glacial till soils analyzed were variable in texture. Clay and sand contents were higher in the till than in the lacustrine soils.

Soil water retention, bulk densities and hydraulic conductivities of representative soils are given in table 15, in appendix. Lacustrine and glacial drift soils retained from 10 to 46 percent water by weight at 0.3 atmospheres tension. The sandy beach soils had a much lower water content at the same tension, and smaller water content differences between 0.3 and 15 atmospheres of tension, indicating that these soils are much more drouthy. Most farmers seed such soils to grass for use as either hay or pasture.

The bulk density of lacustrine and beach soils ranged from less than 1.0 at the surface to about 1.4 below the surface. Glacial drift soils had bulk densities up to 1.8.

Hydraulic conductivities, evaluated by various methods, were variable, usually being greater at the surface and decreasing with depth (table 15). Glacial till soils had low hydraulic conductivities whereas lacustrine soils generally had higher hydraulic conductivities and thus appeared much more drainable.

Specific yields and bulk densities of soils at three sites are given in table 16, in appendix. The soils are lacustrine but, in profile 13, glacial washed sand was at a depth of 63 inches at NE¼ sec. 9, T. 151 N., R. 52 W. (Oakville Township). The specific yields of these soils were low, indicating that a small amount of water entering or leaving the soil would have a significant effect on the water-table level.

DEEP GROUND WATERS

Artesian Conditions

General

The problem area has both flowing and nonflowing artesian wells (fig. 9). These wells vary in depth from 20 to 350 feet, most of them penetrating into an artesian aquifer, but some terminating in the lake sediments or glacial drift. Among the latter are shallower wells. There are two sources of water for the artesian wells—the Fall River and Lakota formations in the Dakota Group (Cretaceous age) and the sandstones of the Winnipeg Group (Ordovician age) (*48*). The average overall thickness of the Dakota Sandstone aquifer in Grand Forks County is about 100 feet with the greatest thickness in the western half of the county. The saline area is in the eastern half. The hydraulic gradient of the Dakota Sandstone aquifer is approximately 5 ft/mi with the hydraulic head decreasing to the east (*29*).

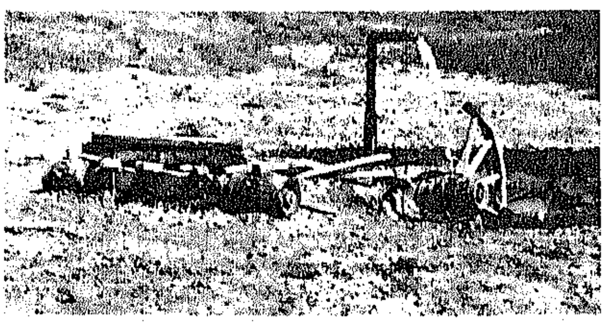


FIGURE 9.—A flowing artesian well in Grand Forks County.

A survey of 80 domestic wells in or near the study area evaluated well depths, artesian pressures, water composition, and other factors. Some of these data are given in table 17, in appendix. Reliability of the pressure measurements was considered good even though some well casings were in poor condition. Both ground surface contours and piezometric contours are shown in figure 10. The plotted curves show there were no flowing wells, that is, the piezometric surface contours were lower than the ground surface contours in the areas adjacent to the Red River and in the southwest study area above the 900-feet ground surface elevation (*5*).

Several wells in the most saline area were over 200 feet deep and had a pressure head between 20 to 30 feet of water column above the ground surface. Most of the wells had pressures of less than 10 feet of water column above ground surface and were also less than 200 feet in depth. Flows of artesian wells ranged considerably. The highest flow in the study area was 36 gal/min but most of the wells had flows of less than 5 gal/min. Kelly and Paulson (*29*) found that average flows in Grand Forks County were about 2

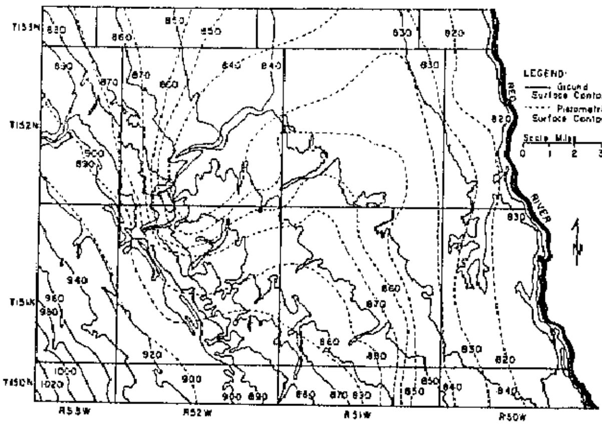


FIGURE 10.—Ground surface elevations (contours) and piezometric surface elevations (contours) as obtained from domestic well data.

gal/min. Low flows are expected for several reasons, namely (a) short screen lengths in the well or no screen at all in the aquifer, (b) flow intentionally restricted because large flows are not necessary to provide an adequate livestock water supply, (c) corrosion, scale buildup or deterioration of well casings, (d) use of small diameter well casings, and (e) a regional head decline over the years (*29*).

Leaky conditions between the artesian aquifer(s) and the ground surface could result in a contribution of artesian water and salts to the water table and the soil profile. The amount of this leakage is dependent on the artesian head in the aquifer and the hydraulic conductivity of the formation(s) between the aquifer and the ground surface.

Where upward seepage takes place through several confining strata, the magnitude of this seepage can be evaluated by applying Darcy's (*18*) equation to flow through n horizontal strata in series,

$$q = \frac{h}{\left(\frac{k_1}{b_1} + \frac{k_2}{b_2} + \ldots + \frac{k_n}{b_n}\right)}$$

where h is the elevation of the piezometric head existing in the artesian aquifer above the water table, k_n and b_n are the hydraulic conductivities and thicknesses, respectively, of each of the n strata overlying the aquifer, and q is the upward flow per unit of horizontal surface area (*36*).

Assuming a homogeous confining strata with a thickness equal to the well depth, the rate of upward leakage can be computed by using Darcy's equation $q=ki$, where

q = flow rate, in/hr
k = hydraulic conductivity of the material overlying the aquifer, in/hr
i = the hydraulic gradient, ft/ft.

For example, at SE¼ sec. 5, T. 151 N., R. 51 W., the well depth is 235 feet, the piezometric head is 26 feet above ground surface and the average water table is 8 feet below ground surface. If the hydraulic conductivity (k) is taken as 0.01 inches per hour or 0.24 in/d, then:

$$q = 0.24 \left(\frac{26+8}{235-8}\right) = 0.036 \text{ in/d}$$
$$= 0.36\ (30) = 1.08 \text{ in/mo}$$

Similarly at SE¼ sec. 30, T. 152 N., R. 51 W., the well depth is 124 feet, the piezometric head is 21 feet above ground surface and the average water table is 9 feet below ground surface. Again, if k is 0.01 in/h, then:

$$q = 0.24 \left(\frac{30}{115}\right) = 0.063 \text{ in/d}$$
$$= 0.063\ (30) = 1.88 \text{ in/mo}$$

Using the assumed hydraulic conductivity of 0.24 in/d, the indicated upward leakage of artesian water would be greater than 22 in/yr. In this case, water tables would remain high throughout the year and the area could conceivably be a swamp. Since it is not a swamp, the hydraulic conductivity is less than 0.24 in/d.

Fluctuations of the water table occur during the summer months because of precipitation, temperature, and evapotranspiration, which in turn is influenced by osmotic pressure of the soil solution. During the winter months, however, one would expect a high water table to remain high. Precipitation effects on water table position and evapotranspiration would be negligible. Hydraulic studies have shown that ground water behavior is as expected during the frost-free season, but it does not behave as expected during the winter months. Cold temperatures and freezing cause a drop in the water table because of ground water being translocated upward toward the colder soil. A cold soil holds more water than a warm soil.

An overwinter experiment conducted within the saline area (SW¼ sec. 11, T. 152 N., R. 51 W.) indicated that soil water increases in the upper 9 feet were greater than the contribution from the upward movement of water table ground water (*10*). Up to approximately 0.3 in/mo of water in the soil profile was not accounted for unless it came from precipitation, lateral ground water flow or upward artesian leakage. The areal ground water table was essentially flat when the soil was frozen indicating that artesian leakage was apparently the primary contributor.

If we assume the entire 0.3 in/mo came from artesian leakage, then k in the formula $q = ki$ can be evaluated. Using an artesian head of 21 feet, a water

table 9 feet below ground surface, and a well (aquifer) depth of 124 feet, then:

$$k = \frac{q}{i} = \frac{0.01}{\left(\frac{30}{115}\right)} = 0.038 \text{ in/d}$$

$$\text{or } \frac{0.038}{24} = 0.0016 \text{ in/h}$$

This calculated k is much lower than most of the measured values shown in table 15, in appendix.

More recently, evaluations from pump test data have shown k to be approximately 0.01 in/d and an upward flow contribution from the artesian source of 0.5 in/yr (*20*). For additional discussion, see Deep Well Pump Test section.

Laird (*30*) and Benz and others (*5*) found that wells penetrating into the artesian formations had sufficient head to flow at ground elevations below 900 feet above sea level. No continuous record over a long period of years has been kept of any artesian well flows or pressures. Such information would be of help in determining whether changes in the artesian formation piezometric head has occurred over the years. Kelly and Paulson (*29*) state that a decrease in piezometric head has taken place in Grand Forks County.

A decline of the artesian head in Dakota Sandstone wells was observed in LaMoure and Dickey Counties in southern North Dakota. Meinzer and Hard (*33*) reported that the piezometric surface contour decreased from an elevation of 1,800 feet in 1886 to about 1,500 feet elevation in 1923 in the Edgeley quadrangle. The belt in which flowing wells were originally obtained but in which the wells ceased to flow at the end of 37 years averaged 7.5 miles wide. The artesian head dropped rapidly from 1902 to 1915, the period of most active well drilling, but not as rapidly from 1915 to 1923.

In 1923, there were approximately 0.5 flowing artesian wells per square mile (2 square miles per well) in an area about 8 miles wide east of the belt of nonflowing artesian wells. These wells were responsible for shutting off the flow in the 7.5-mile wide belt to the west. As a result of legislative action (*47*), artesian water conservation measures reduced the decline in the piezometric surface. A balance was approached between the withdrawal of water from the artesian basin and the recharge (*53*). Saline water resources are fairly abundant in the state but generally are quite deep (*39*).

Piezometer installations

Individual piezometer hydraulic heads and observation well water levels at 13 locations in Grand Forks County are illustrated for June 15, 1959 (fig. 11) and March 14, 1967 (fig. 12). At each location there were usually piezometers terminating at depths of 60, 40, and 20 feet. Four of the locations in figure 11 are duplicated in figure 12.

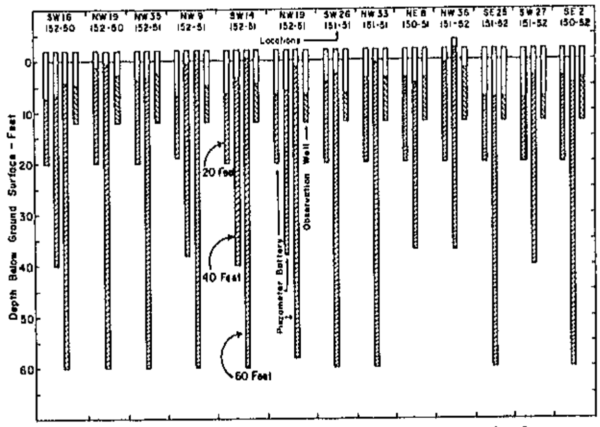


FIGURE 11.—Water levels in piezometers and observation wells at 13 locations on June 15, 1959.

With few exceptions, all piezometer batteries indicated upward hydraulic gradients. Observation wells indicated that water-table depths were usually similar to the pressures shown in 20-foot piezometers. Hydraulic heads in the deeper (60 feet or greater) piezometers remained relatively constant, but in the shallower (30 feet or less) piezometers, hydraulic heads fluctuated considerably, apparently influenced by surface hydrologic and climatic conditions.

Hydraulic head losses occurred vertically upward in the soil profile as shown by measured water heads in the piezometer batteries (table 18 in app.). Generally, greatest head losses occurred in the deeper (60- to

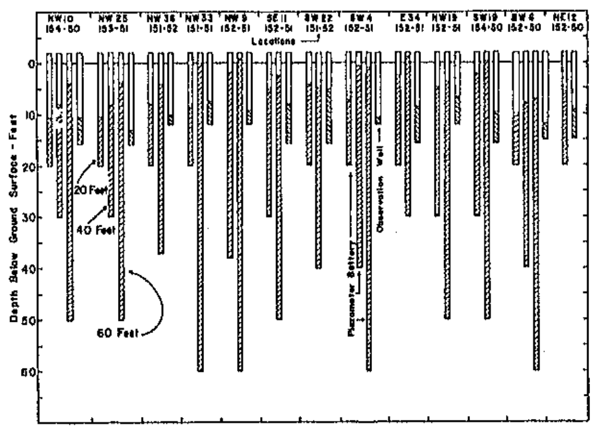


FIGURE 12.—Water levels in piezometers and observation wells at 13 locations on March 14, 1967.

40-foot) soil increment as compared to the shallower (40- to 20-foot) depth, although a clear pattern was not apparent. Averaging the values shows that for a depth increment of 46 to 27 feet from ground surface a vertical head loss upward of 2.8 feet occurred; a gradient of 0.14 ft/ft. Thus, piezometric gradients in the materials overlying the aquifer indicate a potential movement upward of the water and dissolved salts into the overlying materials (5).

Chemistry of Deep Waters

The chemical composition of all artesian waters was similar but varied somewhat in concentration. Table 19, in appendix, lists the chemical composition of water from some artesian wells including one nonartesian well (listed last). The artesian wells ranged in depth from 90 to 248 feet and the nonartesian well was 40 feet deep. The next to the last artesian well in table 19 is located in Pembina County, a saline area in the northern part of the Red River Valley (fig. 2). This water had a composition similar to the other wells, but the constituents were more highly concentrated. The nonartesian well listed is on the Elk Valley Delta. Water in this well was of good quality, which is typical of wells in the delta area west of the saline area (*27*). It is included here for comparison purposes.

Salinity of the artesian well waters, expressed as electrical conductance, varied from 6.4 to 17.3 mmhos/cm and averaged 8.8 mmhos/cm. This compares with the average EC of 8.6 and 7.9 mmhos/cm in 1957 and 1959 for the wells listed in table 17, in appendix. The range of pH and boron were not great in the artesian wells and averaged 8.1 and 3.1 p/m, respectively. Sodium made up about 70 percent of the cations, followed by calcium and then magnesium. Chloride content was usually higher than sulfates. Sodium-adsorption-ratios (SAR) ranged from 11 to 29 and averaged 18.

A less detailed chemistry of ground water from several piezometer batteries is given in table 20, in appendix. Piezometers were terminated in lacustrine and till materials. They were pumped out before obtaining samples. Ground water at 58 feet in the till and lacustrine sediments generally had a composition similar to that of the artesian waters. This was especially true in the areas of high soil salinity. Salinity and chemical constituents shown in table 20 increased upward in the soil profile.

For example, at sec. 9, T. 152 N., R. 51 W., the salinity at 58 feet was 9.5 mmhos/cm and at 18 feet it was 30 mmhos/cm. The ground water composition changes with depth at sec. 19, T. 152 N., R. 51 W. were just the opposite. Salinity increased from 3.0 mmhos/cm at 18 feet to 6.5 mmhos/cm at 58 feet, with soluble sodium increasing from 19 to 61 at the same depths, respectively. Thus, the general tendency was for ground water to approach a chemistry similar to the artesian water as soil depth increased.

SHALLOW GROUND WATERS

Fluctuations of the Water Table

Average annual water-table levels in the study area over 9 years ranged from 4 to 8 feet below ground surface (fig. 13). A seasonal pattern, affected primarily by precipitation (*5*) was a high water table that fluctuated during periods of high rainfall and high consumptive use (spring and summer); then in late summer, fall, and overwinter the water table receded and usually reached its lowest level just before the spring thaw. Water-table data were not as accurate in the last 6 years as they were in the first 4 years because observation wells were not read as frequently (fig. 13).

The water table was responsive to precipitation and soil temperature (*10*). Usually a rainfall of one-half inch or more caused a rise in the water table. This response was contingent, of course, on antecedent soil-water conditions.

The water-table curves during winter are of particular interest. Because the water table dropped or receded during this season it would appear that upward artesian leakage or lateral flow, or both, do not exist. However, upward leakage from the saline artesian aquifer does exist (*10, 20*) as was discussed earlier.

Water-table depths in high and low soil salinity areas are shown in figure 14. Water tables were always 1 to 6 feet higher in the highly saline areas than they were in the low salinity areas, but patterns of fluctuations in each were similar.

Water-Table Profiles

Two approximately parallel east-west profiles through the saline area of the ground surface, water table, and piezometric heads from domestic artesian wells and at depths of 20 and 60 feet are illustrated in figures 15 and 16.

One cross section (fig. 16) traversed the low-elevation Kelly slough that is underlain by a shallow sand

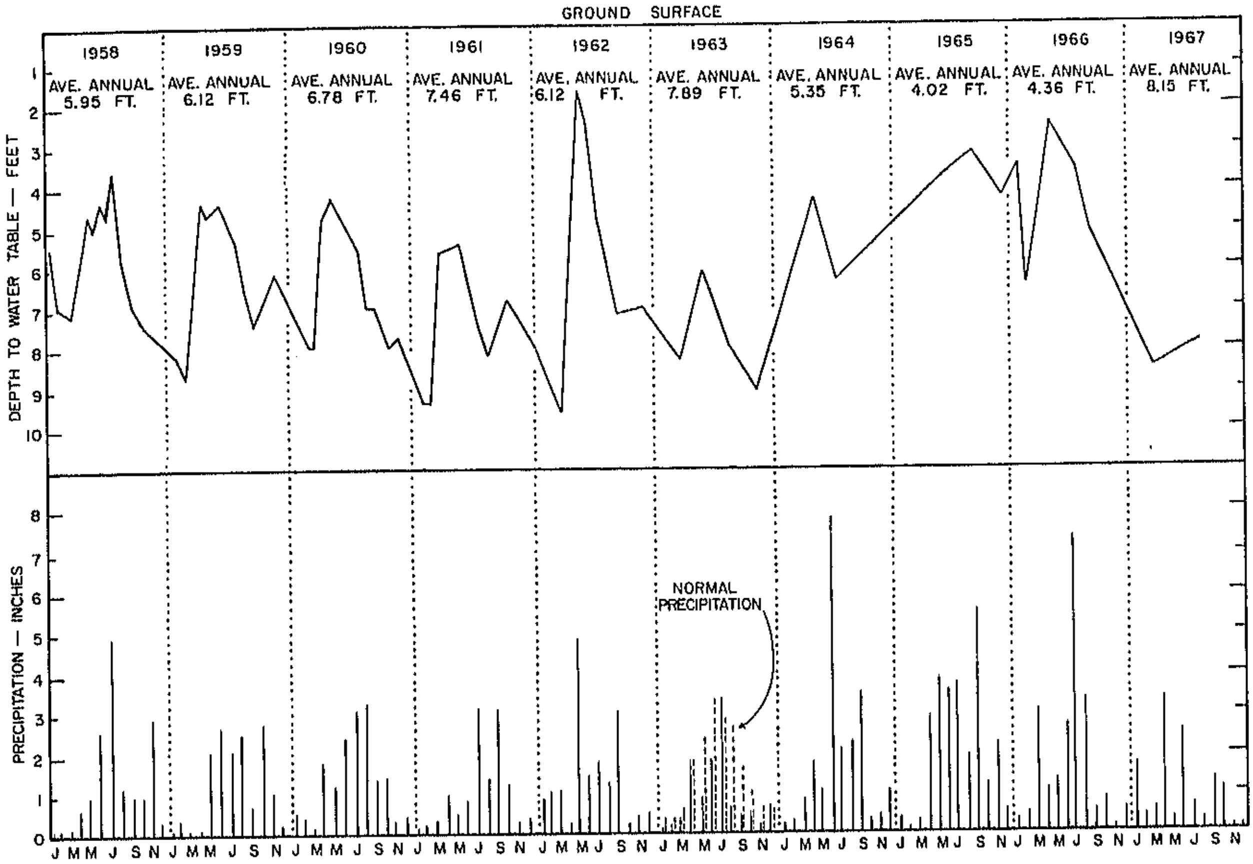


FIGURE 13.—Average water tables and monthly precipitation in the study area during 9 years.

aquifer containing saline water under pressure. The sand layer extends to the east thus the formation could contribute saline artesian water into the eastward-lying area. Jetting and drilling logs, however, indicated that the sand formation is pinched off and increased in depth to the east; thus, there is probably no effect on the saline ara.

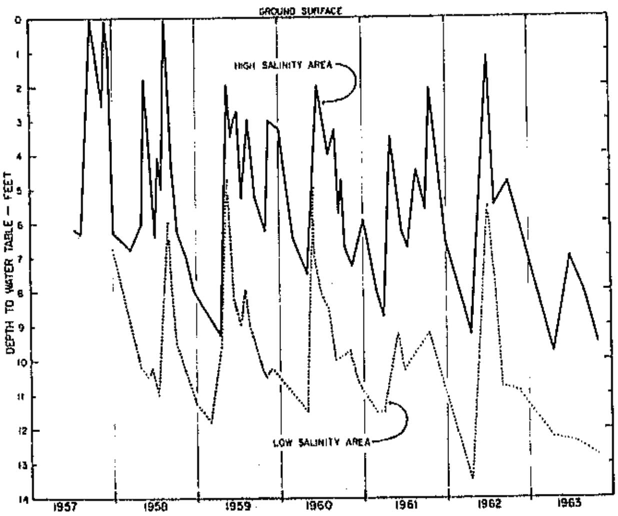


FIGURE 14.—A comparison of study area 7-year average water tables in highly saline (> 10 mmhos/cm) and moderately saline (< 10 mmhos/cm) sites.

Piezometric profiles showed an upward flow gradient with greatest pressures occurring in the most

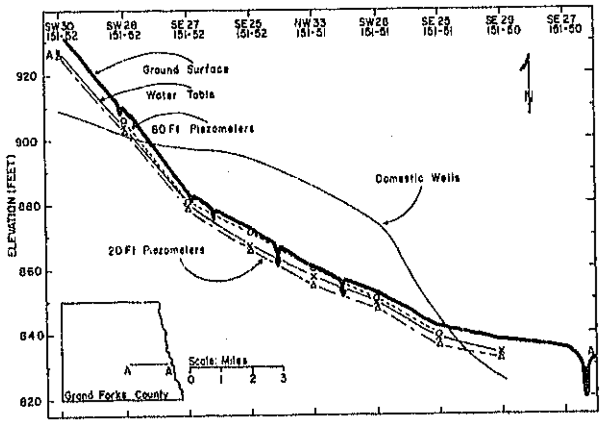


FIGURE 15.—Ground surface, water table, and piezometric pressure profiles in the south cross-section of the study area on October 10, 1966.

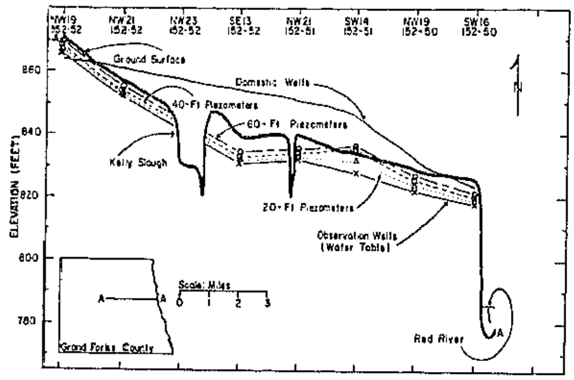


FIGURE 16.—Ground surface, water table, and piezometric pressure profiles in the north cross-section of the study area on October 10, 1966.

saline area. The profile of domestic wells shows a high pressure in the saline area. The cross sections also indicate that the Red River water level was much below that of the water table in the lake-plain area.

Vertical upward flow is also shown in a northeast-southwest diagonal cross section across the saline area (fig. 17). The three, southwestern, deep piezometers terminated in glacial till and the two in the northeast terminated in lacustrine sediments. A deep piezometer (40 or 60 feet), a 20-foot piezometer, and a shallow observation well were installed at each of the five locations shown. The piezometers indicated pressure whether in glacial till or lacustrine sediments.

A northeast-southwest profile of the ground surface, water tables, plus 20-foot and domestic well piezometric surfaces on two dates, are shown in figure 18. The July water levels were high, averaging about 3 feet because of above normal precipitation. In November, the average water table was about 7 feet

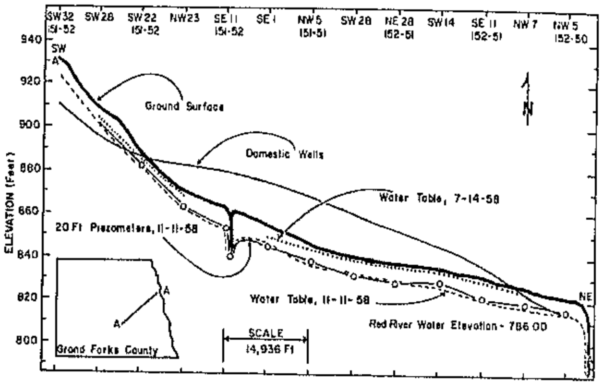
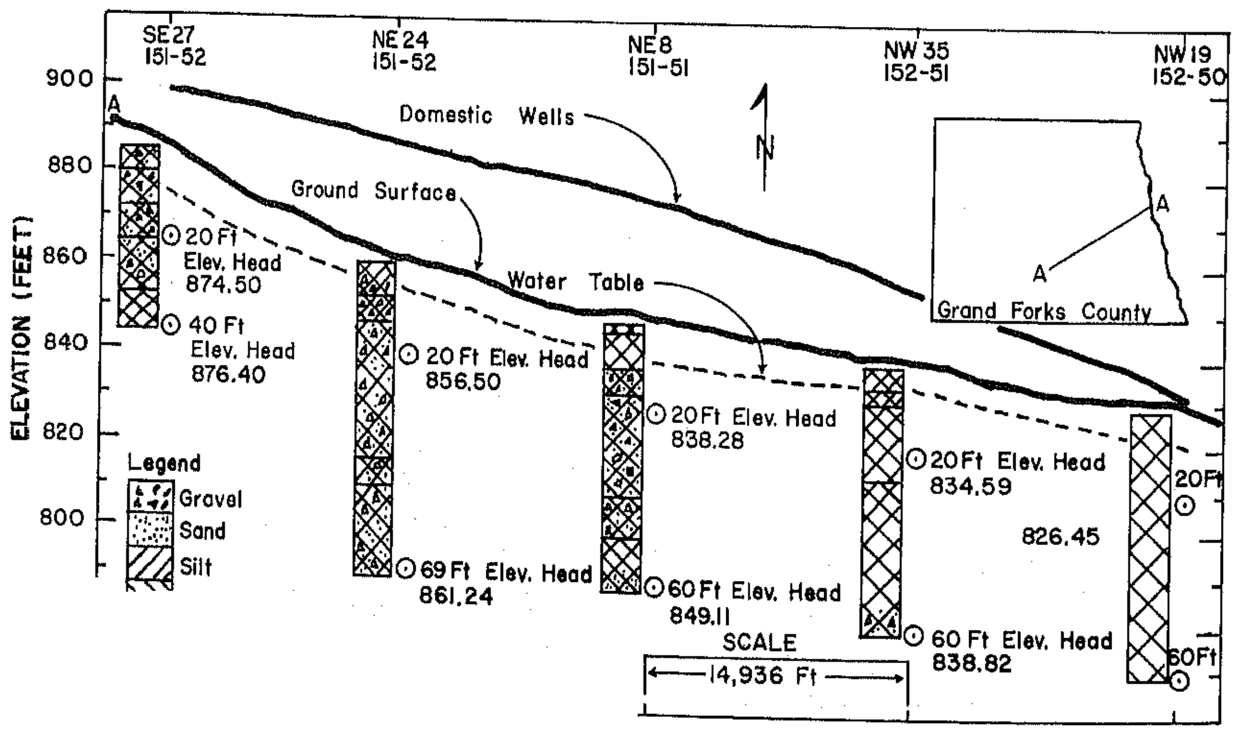


FIGURE 18.—Ground surface, water tables, domestic wells pressures, and 20-foot piezometer water levels on July 14 and November 11, 1958, across the slope, southwest to northeast in the study area.



estic wells pressures; and piezometer soil logs and
f deep piezometers in the study area.

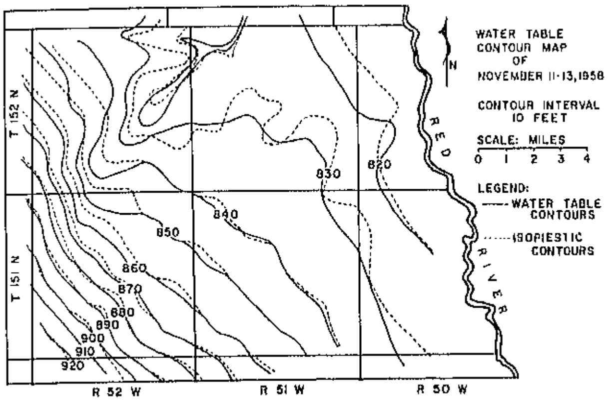


FIGURE 19.—Water table and 20-foot piezometer water levels contour map of the study area.

deep. Water levels in the 20-foot piezometers were comparable to those in the observation wells (allowing for response time), but they were slightly higher in the areas of highest salinity. The water table in the steeper slope area (southwest) was more than 1 foot shallower on the average than it was in the flatter area to the northeast. The potential for vertical upward flow is shown graphically in figures 15 through 18 by the high heads exhibited in domestic wells. These areas are also the most saline. The large difference in head between the deep piezometers and the domestic well heads indicate a high head loss in the intervening formations.

The glacial till soils in the southwestern area have extremely low hydraulic conductivities—lower than those of the lacustrine area to the northeast. The differences in hydraulic conductivity would indicate little lateral movement into the lacustrine area from the till area.

Water-Table and Isopiestic Contours and Isobaths

Water-table contour maps illustrate slope of the water table and thus the direction of horizontal ground water movement. These data were obtained from shallow observation wells. Water levels in 20-foot piezometers were also plotted to compare ground water flow at the 20-foot depth with water-table flow.

A map of water table and 20-foot piezometric pressure levels is given in figure 19 for November 12, 1958. Generally, the isopiestic lines follow the same pattern and have the same slope characteristics as the water-table contours. Water levels in 20-foot piezometers were usually slightly higher compared to water levels in shallow observation-wells.

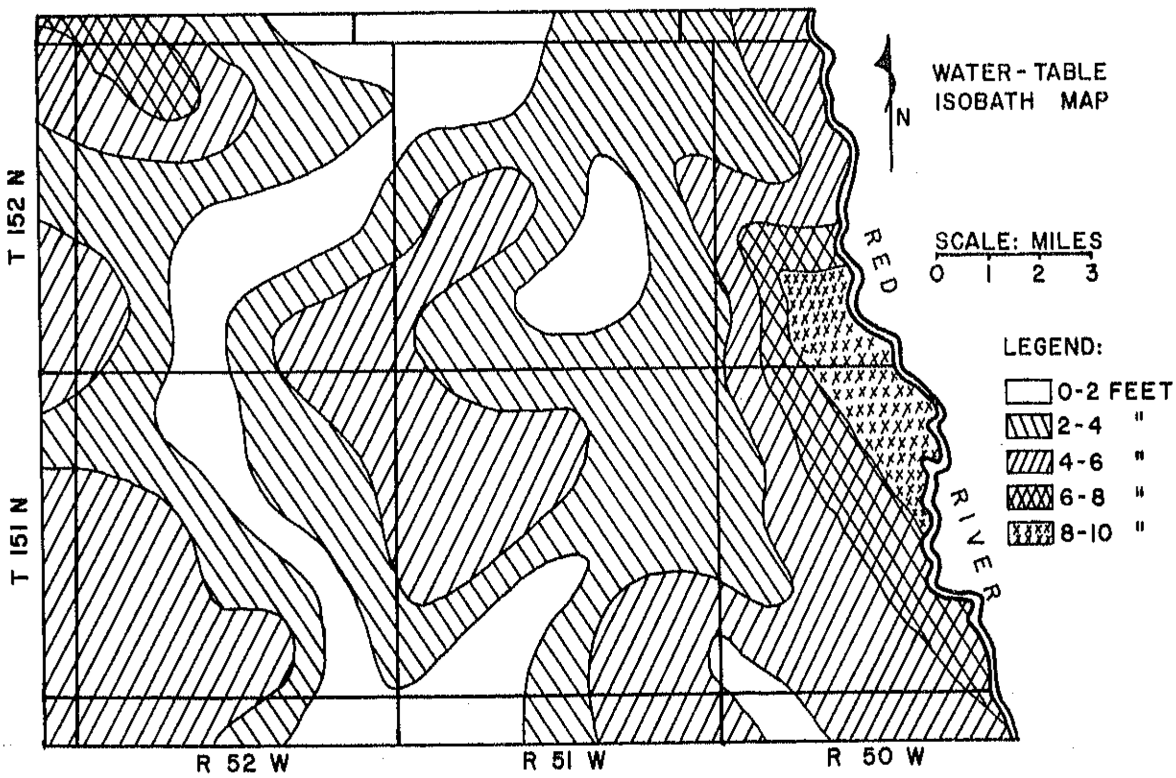


FIGURE 20.—Water-table isobath map of the study area in a high water table period.

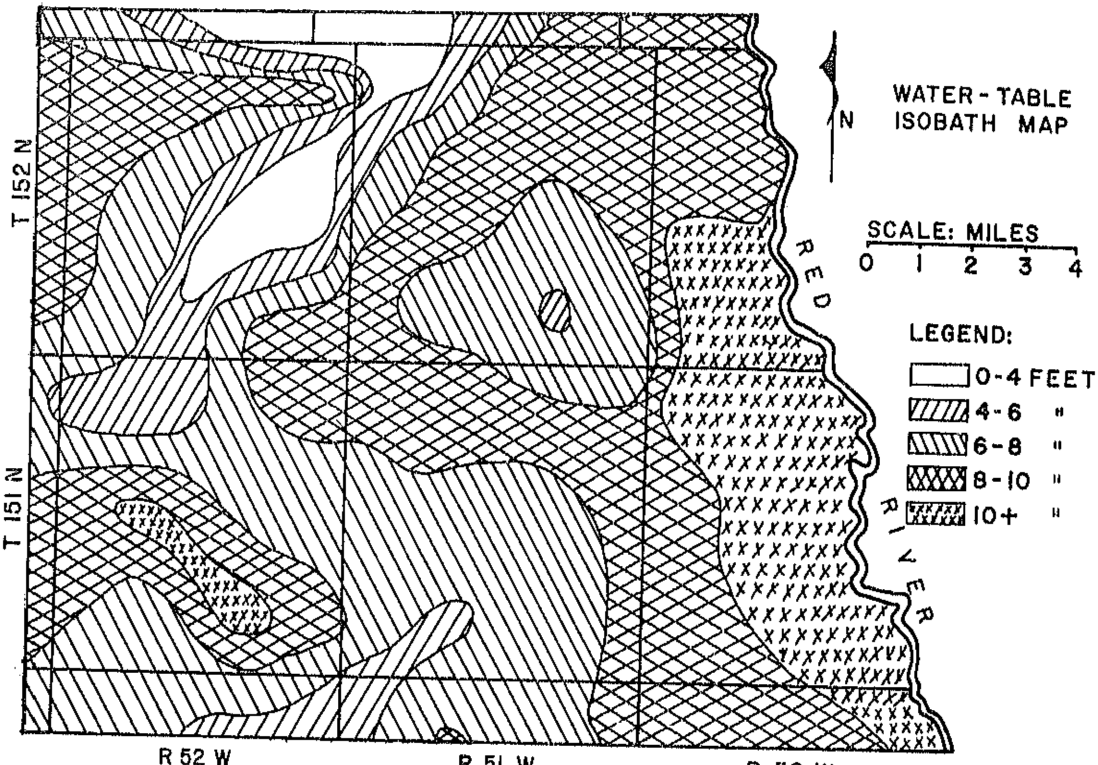


FIGURE 21.—Water-table isobath map of the study area in a low water table period.

Water-table isobath maps are useful in providing graphic information on the adequacy of drainage. They show water-table depth below ground surface on an areal basis and thus areas in which artificial drainage may be required. Information for such maps is obtained from shallow ground water observation wells. Two water-table isobath maps, in figures 20 and 21, portray areal water-table depths on two days, when the water table was high (fig. 20, July 12) and also when it was low (fig. 21, November 12). Precipitation was 2 inches below normal, but July and November precipitation was about 2 inches above normal. The areas requiring drainage (highest water tables) generally coincided with areas of high soil salinity (see fig. 4).

Effects of Surface Drains

The usefulness of natural and artificial surface drainage was evaluated by studying drawdown characteristics of the water table adjacent to existing drains.

Water tables measured on three dates are illustrated in figures 22 (a constructed drain) and 23 (a natural drain). Limited beneficial effects of water-table drawdown are shown. However, no beneficial effects because of soil salinity reductions were observed by visual inspection of crop responses. Where road ditches do not have a gradient, the standing saline water is detrimental to the adjacent land. Thus grading road ditches so they will drain would be a beneficial practice in the saline areas and in adjacent areas as well.

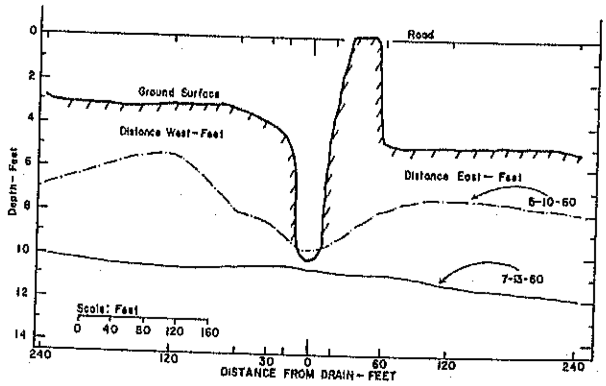


FIGURE 22.—Ground water (water-table) profile, on several dates, normal to an artificial surface drain at the ¼ line of sections 33 and 34, T. 154 N., R. 52 W., in a saline area.

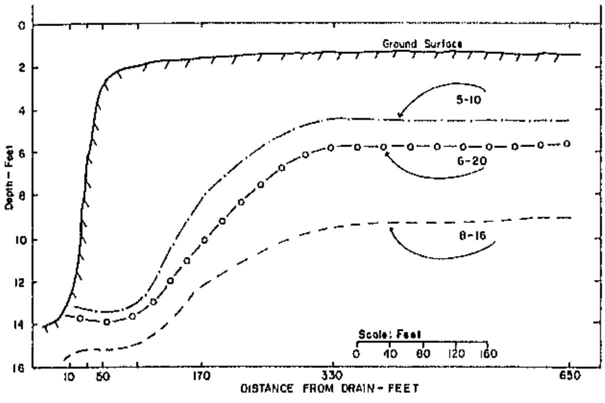


FIGURE 23.—Ground water (water-table) profiles, on several dates, normal to a natural drain (Freshwater Coulee) at common corner of sections 13, 14, 23, and 24, T. 151 N., R. 52 W., in a saline area.

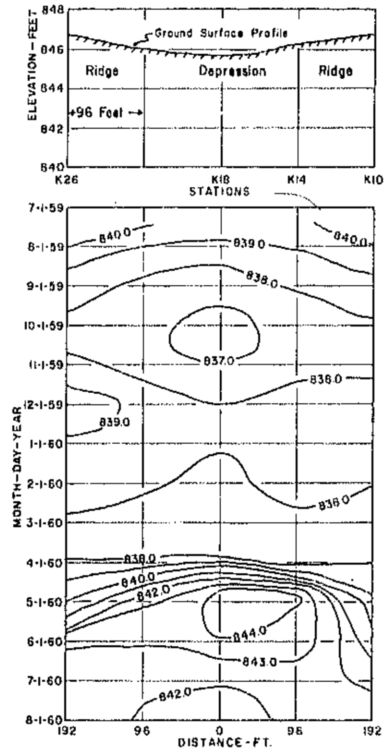


FIGURE 25.—Water-table isopleths for a 384-foot soil profile cross section between two ridges and through a depression during July 1, 1959 to August 1, 1960 at NE¼NW¼ sec. 8, T. 151 N., R. 51 W.

Ridge-Depression Ground Water Movement: Shown by Isopleths

The phenomenon of saline ridges and adjacent nonsaline depressions within the saline area are explained by the two diagrammatic flow sketches shown in figure 24. During the drying cycle, greater evapotranspiration occurs in the depression because it is nonsaline and there is better plant growth and lower soil temperature; as a result, the water table is lowered. In the wetting cycle, precipitation sometimes runs off the ridge into the depression and raises the water table of the depression. Infiltration is higher and thus there is more leaching of salts from the soils in the depressions compared to the ridges. The upward flow of artesian water with its salt load occurs during both cycles and under both the ridges and depressions because it is a regional phenomenon. This is in contrast to a local phenomenon taking place through precipitation-caused flow down to 20-foot depths in the ridges and depressions.

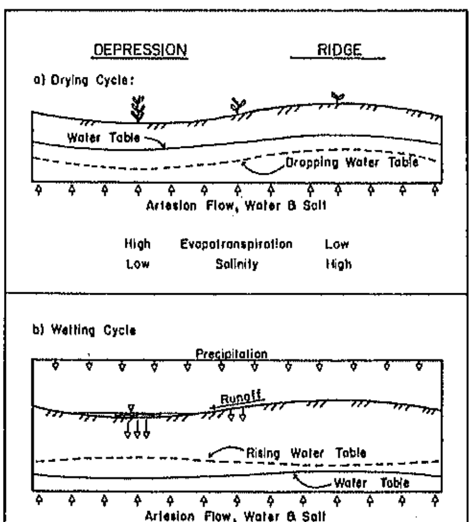


FIGURE 24.—Diagrammatic sketches of the hydrologic flow regimes by (a) a drying cycle, and (b) a wetting cycle which creates the nonsaline depressions and saline ridges.

In a study of the movement of this water through the soil, water-table isopleths (37) show graphically the large seasonal variations of the water table (see Topography, Relief, and Drainage) in time and in space. The water-table isopleth has a time scale on the ordinate and a vertical cross section through a series of observation wells on the abscissa. Thus, the graph shows a change of water-table elevations with time through a soil cross section.

The water-table isopleth shown in figure 25 represents a cross section 384 feet long from the crest of a saline ridge, through a nonsaline depression to the crest of another saline ridge. The period covers a year

and shows a recession of the water table in the depression from July to April. During this same period—in particular, from November to January—the depressional ground water mound caused a rise in the water table under the ridges. On April 1, the water table was essentially flat—the water table had leveled off in the soil cross section—but spring snowmelt then brought about a sharp rise in the water table and a subsequent formation of the ground water mound in the depression. The figure shows, in general, that water-table fluctuations in the depressions were rapid and pronounced with large variations taking place. These fluctuations were always less under the ridges.

Additional data from the shallow ground water regime in this saline ridge-nonsaline depression microrelief area (*6, 40*) indicates that ground water movement and soil salinity were affected by: (a) surface relief causing impounding of precipitation in the depressions and consequent leaching of salts (leaching was effective to depths greater than 20 feet); (b) higher hydraulic conductivities in the depressions which permitted water to move faster through the soil, but apparently not much movement occurred through the ridges and thus the result was probably a series of semi-enclosed systems; and (c) differential water use primarily as a result of lower soil salinity in the depressions.

The deep ground water regime indicated the presence of artesian pressures and thus a potential for vertical upward leakage of saline artesian waters. Pressures were not high but sufficient to sustain the water table. With leaching occurring in the depressions, the ridges become salt sinks. Shallow ground water salinity in the depressions of the 10-acre study area was less than 4 mmhos/cm, but in the ridges it exceeded 11 mmhos/cm. Water-table fluctuations in ridges and depressions were similar, but fluctuations were smallest in the ridges.

Agronomic Cultural Effects on the Water Table

Land-use affected water-table position and soil salinity in the saline, high-water-table areas. In a study to find out what happens when an area is summer-fallowed compared to growing grain or grass (*44*), results show the water table during the growing season was highest under fallow and about one-half foot lower under the grass (fig. 26). The water-table depth under barley was between the depths for grass and fallow. Precipitation caused water table rises during the season. June rainfall was about 1 inch below normal, but May, July, and October rainfall was about one-half inch above normal. January, March, and

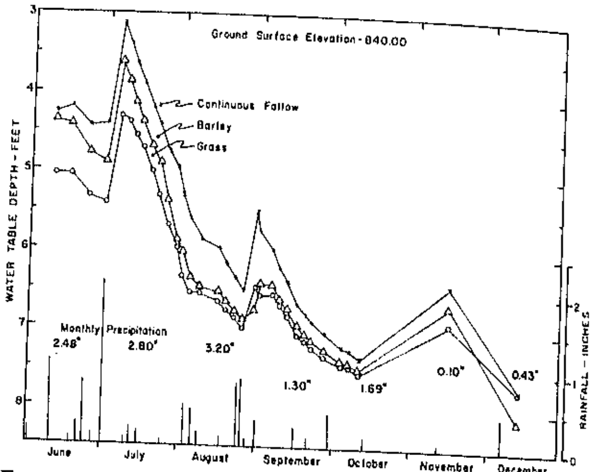


FIGURE 26.—Water-table fluctuations under three land use treatments and precipitation in 1960 at SW¼ sec. 34, T. 152 N., R. 51 W.

December precipitation was slightly below normal leaving an annual deficit for the year of about 1½ inches. Growing season precipitation was approximately normal and, thus, the water tables were also at a to-be-expected normal—or at depths and trends that would occur in an average year. Despite short horizontal distances between different land use plots, there was a distinct difference in water tables. This indicates that horizontal drainage or flow was slow.

The phenomenon of different water tables under different soil surface treatments also occurred over winter and apparently resulted from freezing effects (*8, 10*). Depths and rates of soil freezing were greater under bare soil than under a straw mulch.

Diurnal Fluctuations of the Water Table

Todd (*49*) discussed the diurnal fluctuation phenomenon and attributed it to evaporation or transpiration, or both.

Diurnal fluctuations of the water table in a relatively nonsaline depression in the ridge-depression microrelief area is illustrated in figure 27. Evapotranspiration can be expected to be high because the shallow observation well was located in the center of a 10-row shelterbelt. No precipitation events occurred during the 4½ days. The diurnal fluctuations occurred with the water table more than 8 feet below ground surface. Soil temperatures were not taken; temperature-caused diurnal fluctuations of the water table at the 8-foot depth were not likely.

The water table in the two adjacent saline ridges—at horizontal distances of 400 and 800 feet—was at an elevation of 839.6 feet on July 27 and at 839.5 feet,

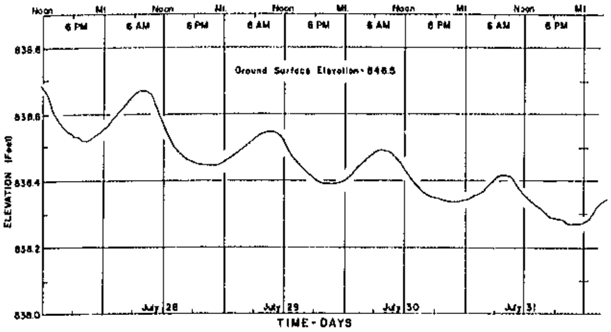


FIGURE 27.—Diurnal fluctuations of the water table in a 12-foot observation well located in a field tree shelterbelt at NE¼NW¼ sec. 8, T. 151 N., R. 51 W., during 4 days in July 1959.

July 31. Ground surface elevation of the two ridges was about 0.6 foot higher than the depression. No diurnal fluctuations occurred on the ridges, which were almost devoid of tree growth because of high soil salinity.

Maximum water-table levels in the depression, during 1 day, occurred at about 8 a.m. and minimum levels took place at about 8 p.m. These maximum and minimum water-table levels represent temporary equilibrium points between discharge because of evapotranspiration and recharge from surrounding ground water. Average maximum and minimum air temperatures for 5 days were 89° and 63° F.

The total quantity of water withdrawn by evapotranspiration in a given day can be computed (*54*) when crop or tree cover is uniform and when osmotic pressure of the soil solution is not limiting. Assuming that evapotranspiration is negligible from midnight to 4 a.m. and that the water table during this period is the mean for the day, then the hourly recharge from midnight to 4 a.m. can be taken as the average rate for the day. Thus,

$$Q_{et} = S_y\ (24H \pm s),$$

where Q_{et} = depth of water withdrawn from ground by evapotranspiration during 24 hours,
S_y = specific yield of soil at water-table depth,
H = hourly rate of change of water table between midnight and 0400 hours, and
s = net rise or fall of the water table during 24 hours.

Qet, H and s are in inches, feet or any consistent system of measuring units. The total ground water discharge on July 28, 1959, can be calculated using a specific yield of 2 percent (from table 16).

$$24H = 0.40 \text{ feet and}$$
$$s = +0.10 \text{ feet, therefore,}$$
$$Q_{et} = .02\ [0.40 + 0.10] = 0.01 \text{ ft/d or } 0.12 \text{ in/d.}$$

If we assume a specific yield of 20 percent, then the total ground water discharge becomes 0.10 feet per day (ft/d) or 1.2 in/d. The above relationship gives an approximate value because the rate of ground water recharge to the depression depends upon the water table surrounding the well area.

Lateral Ground Water Movement

The probability of shallow ground water flow from regions of high elevation to low elevation always exists in valleys and areas where geologic and surface conditions encourage it. Such flow may occur as overland surface flow, as below surface lateral flow, or as deep seepage.

Two or more possible sources of shallow ground water could recharge into the saline high-water-table area. These are the shallow nonsaline ground waters (*1, 27*) in the relatively permeable Elk Valley Delta deposits to the west and the glacial till materials that are also to the west but extend into the saline area. Both materials are at higher elevations than the lake deposits, but probably neither make a significant contribution of ground water flow into the saline area compared to flow from the underlying artesian formations. Drainage or flow from Elk Valley Delta would flow through the till and along seepage faces or permeable lenses (layers) in the till. If this were taking place, then the shallow ground water in the lake-plain saline area should be of low salinity and have a chemistry somewhat similar to that of the shallow ground water in the Delta that is of good quality; however, this is not so.

Surface drainage in the Delta is good and ground surface slopes are 15 to 20 ft/mi. Thus, excess surface waters usually find their way into streams and drainageways traversing through the Delta, till, and lake-plain areas.

Contributions of ground water flow from the till and beach area lying above the saline till and lacustrine area are also possible. The ground surface slope is higher in the till area than it is on the lacustrine plain. Thus, if hydraulic conductivities were the same in the till and the lacustrine materials, there would be a potential for ground water flow into the lower-lying flatter area. This is probably not happening, however, because the higher ground slopes and consequent higher hydraulic gradients in the till as compared to the lake plain are offset by the higher hydraulic conductivities in the lacustrine soils.

For example, the hydraulic gradients are 10 feet and 3 ft/mi in the till and lacustrine areas, respectively, whereas the hydraulic conductivities are about

0.003 and 0.010 ft/h, respectively, in the till and lake plain. Using these values of hydraulic gradients and conductivities, the lateral flow through the till and lacustrine areas would be equal, and the amount of flow through a square foot of soil would be 5.7×10^{-6} cubic feet per hour.

However, lateral seepage into the saline area is possible through permeable strata or layers, contact zones, and cleavage planes, in the till as well as in the lacustrine area. For example, in all soil profiles examined which had till at less than 12 feet from the surface, there was a washed, coarse-textured contact zone 2 to 24 inches thick between the till and lacustrine sediments (see table 12).

Seepage also occurs from old abandoned artesian wells with corroded casings and from past and present flowing wells that discharge saline water on the land. Most artesian wells have not received proper care. Flowing wells were not shut off when not being used, corroded casings were not repaired or replaced, and large flows were not reduced to provide only an adequate supply. As a result of these conditions, much saline artesian water has flowed into the land contributing to localized saline conditions.

Chemistry of Shallow Ground Waters

General chemical composition

The chemistry of shallow ground waters is variable with a wide range in composition and concentration (tables 21 and 22 in app.). Observation wells listed in table 21 were cased with 4-inch coal-tar-impregnated fiber pipe; those listed in table 22 were open uncased holes. Chemistry of the waters in both types of wells was similar but the data are more detailed in table 21. These observation well locations are shown in figure 8. The bottom group in table 22 were sampled from an area north of the Turtle River (see fig. 6). These well locations cross saline land on which detailed studies were not conducted.

Chemical properties of the shallow waters were similar to those of the soils, namely, ground water in the lacustrine sediments had a chemistry similar to that of the lacustrine soil in which it was located (see Soils section—tables 12 and 13 in app.). General water salinity, expressed as electrical conductivity, varied considerably with a high of 58.3 and a low of 1.2 mmhos/cm. Ground water in a lacustrine depression had the lowest salinity, but an adjacent lacustrine ridge had ground water with a salinity of 45.4 mmhos/cm. Waters in the glacial till had a salinity usually comparable to, or a little higher than, that of artesian waters.

Boron was usually higher in the glacial till waters, and water pH (not shown) ranged between 7.7 to 8.0. Magnesium was frequently the dominant cation in the lacustrine areas, and sodium was always predominant in the glacial drift waters. Sulfates and chlorides were present in large quantities, but a definite pattern was not exhibited although chlorides were usually higher than sulfates in the glacial till. The potassium content was less than 1 meq/l (milliequivalent per liter). SAR ranged from 0.7 to 22 with the higher values related to higher salt concentration, but usually SAR was less than 13.

Seasonal Influences

Water samples, obtained in March when the water table is usually low and in July when it is usually high, were used to evaluate salt concentration effects on soil water. Rises in the water table always occur in spring and after high amounts of precipitation. Numerous observation wells and piezometers were sampled during the period studied. Data from these installations, consisting of water-table depths, electrical conductivity, and Na content are given in table 23, in appendix.

The 1958 data show that average ground-water salinity decreased from 15.7 in May to 13.5 mmhos/cm in October. The water table was 4.6 feet in May and 7.4 feet in October. In 1962, general salinity and Na content in the shallow observation well waters remained approximately the same from March to July, even though the average water table rose more than 4 feet. There was little to no change in piezometer water salinity between the two sampling periods.

As stated previously, shallow ground water was usually similar in salt concentration to the ambient soil. Precipitation which infiltrates the soil causes a rise in the water table and influences shallow ground water quality and soil salinity. Soil management can also affect soil salinity as explained later.

Salinity difference between ridges and depressions

Salinity differences between ridge and depression ground water were pronounced, but little change occurred in seasonal salinity of ground water (table 24 in app.). These data are from a study wherein ridge-depression soil salinity and hydrologic interrelationships were evaluated in an area of about 10 acres (*6, 40*). Observation well waters had an average salinity

of 17.3 mmhos/cm in the ridges as compared with about 3.0 mmhos/cm in the depressions. The 20-foot piezometer waters had a salinity in the ridges of 11.6 mmhos/cm as compared with 3.9 mmhos/cm in the depression.

This means that the ground water changed from nonsaline in the depression to highly saline in the ridge. The average distance between depression and ridge centerlines is about 350 feet at this site.

Vertical (upward) ground water gradients were not evident in the surface 20 feet but an upward gradient was indicated between the 20- to 60-foot depths.

Salinity associated with bare soil, straw mulch, grass, and various water-table depths

In a 2-year study comparing bare soil and straw mulch at one site (table 25 in app.) and under grass at another site (table 26 in app.), data on water salinity from observation wells to depths of 7, 9, and 11 or 12 feet show ground-water salinity at both sites was high. Although little to no difference of water salinity occurs in wells of different depths at a particular time, there was often a large difference in water salinity on different dates, for example, March 1 versus July 29, 1963. Either a rise or drop in the water table accompanied this change in salinity.

STREAM WATERS

Chemistry and Streamflows

The chemical composition of some surface stream waters traversing through and adjacent to the saline areas is given in table 27, in appendix, (see fig. 6 for sampling locations). Most of the locations were sampled three times during 1 year.

All of the streams are intermittent except the Red River. The Turtle River is the largest stream in the saline study area that empties into the Red River. The Turtle River was sampled at location No. 1 where it enters the saline area. The data in table 27 show that the water at this point is classified C3-S1 Class (*55*) and thus, would be acceptable as an irrigation water. After the Turtle River has picked up water from drains coming out of the saline area, electrical conductivity increased from 0.8 (location No. 1) to 8 and 12 mmhos/cm (location No. 6) in November 1958 and October 1959, respectively. In June 1958, the water was less saline because of spring runoff. Streams emptying into the Turtle River (locations 2, 5, and 9) were saline. The salinity increase resulted in a deterioration of water quality in the Turtle River.

Waters of the Red River had an electrical conductivity of about 0.7 mmhos/cm. No increase of salt occurred in the Red River in traversing (sampling locations 7, 8 and 12) by or through the saline area.

Streamflows of the Turtle and Red Rivers have been reported by Wells (*51, 52*). At Manvel, sec. 13, T. 153 N., R. 51 W., (location 10), the 22-year average flow of the Turtle River was 49.6 ft^3/s (cubic feet per second) with gage readings of 3, 17, and 23 ft^3/s on November 13, 1958, June 4, 1959, and October 27, 1959, respectively. At Grand Forks, sec. 4, T. 151 N., R. 50 W., (location 8), an 85-year average flow of the Red River was 2,397 ft^3/s with gage readings of 410, 2,080, and 3,300 ft^3/s on the same dates as those given for the Turtle River. The flow of the Red River at Oslo, Minn., (location 11), which is 9 miles north of Manvel and downstream from the Red-Turtle Rivers junction, was 2,250 ft^3/s, June 4, 1959.

MISCELLANEOUS ASPECTS

Consumptive Use

Consumptive use for three crops—alfalfa, bromegrass, and barley—was computed (*12, 19*) and is shown in figure 28. The curves show accumulative consumptive use, accumulative rainfall, monthly consumptive use, and monthly rainfall during the growing season. Vertical distance between the accumul[ative] consumptive curve and the accumulative rainfa[ll] curve at any time during the growing season indicat[es] the shortage of accumulated precipitation up to th[at] time for maximum potential evapotranspiration f[or] the given crop.

The data indicate consumptive use exceeds precipitation, thus, existing high water tables are not [due to] an overabundance of rainfall. However, the[se] ... for no[...] water ...

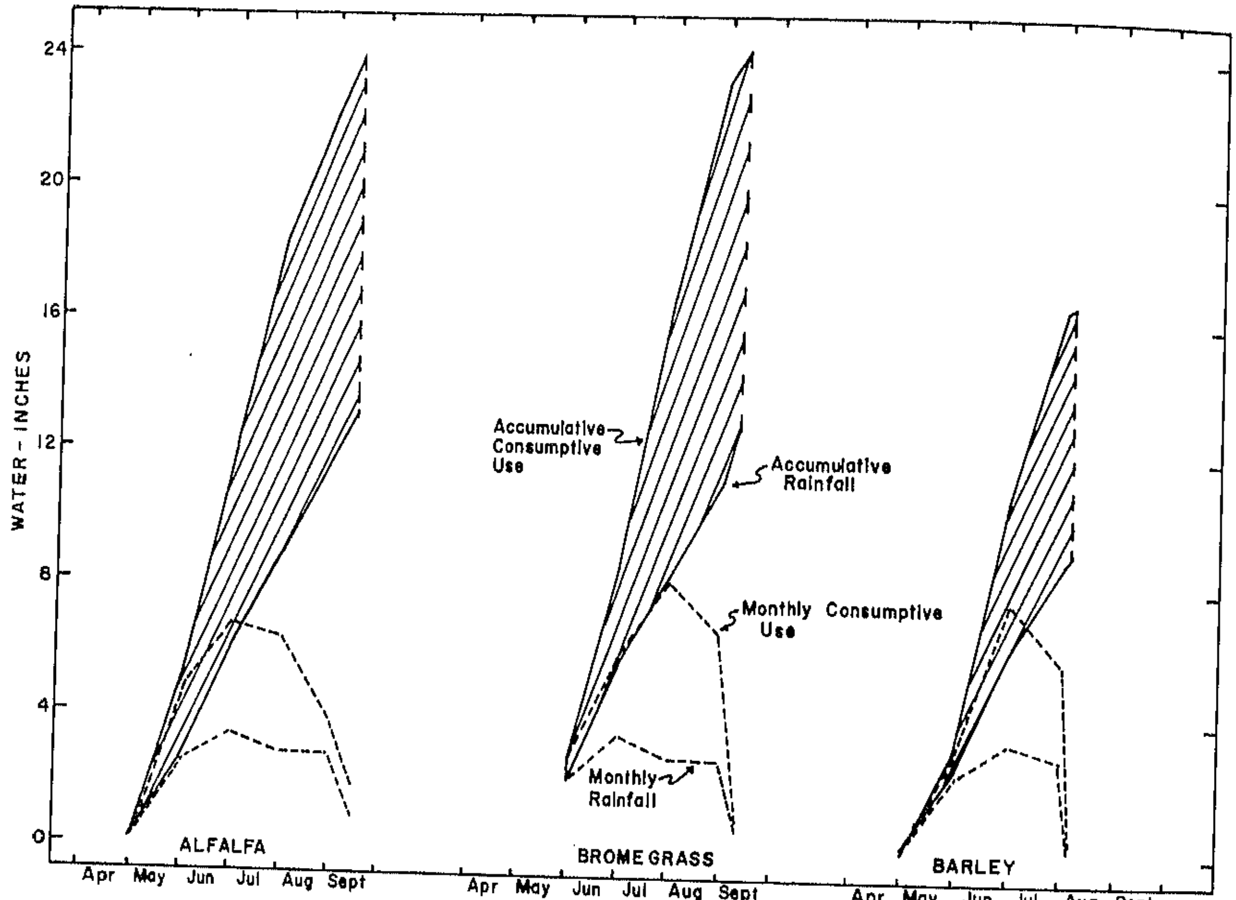


FIGURE 28.—Computed consumptive use of alfalfa, bromegrass, and barley, under nonsaline conditions, for the Grand Forks, N. Dak. area.

Soil-Water Content Related to Soil Salinity and Land Use

To illustrate the phenomenon of soil-water unavailability to plants, a comparison of actual soil-water contents, average salinity in the root zone (0 to 66 inches), and approximate decrease in water availability because of soil salinity in a saline ridge and adjacent relatively nonsaline depression are given in table 28, in appendix, for N½N½ sec. 8, T. 151 N., R. 51 W. (Brenna Township), on August 14, 1958. The area was cropped to barley but growth was poor on the saline ridges because of soil salinity. Soil-water content was higher in the ridges partly because of less evapotranspiration. The calculated data show that soil solution salts were high enough that from 32 to 75 percent of normally available soil water in the ridges was not available for plant use; but, there was no decrease in soil-water availability in the nonsaline depression.

Soil-water stress during the growing season under two land-use treatments indicated that average soil-water tension in the surface 12 inches under fallow was 0.25 bars and about one bar under grass (table 29 app.). Soil-water content under fallow remained at approximate field capacity whereas evapotranspiration was high from the surface foot of soil that was under grass. In this experiment, the summer fallow treatment was effective in reducing soil salinity (*41, 44*).

Surface Soil Salinity and Water-Table Depth Correlation

To evaluate the possibility of a relationship between surface (0 to 6 inches) soil salinity and water-table depths, soil samples were taken monthly (except winter months) at the same time observation wells were read over 3 years. Twenty-four locations were sampled but data are presented on 14, seven grass sites in table 30, in appendix, and seven cultivated sites in table 31, in appendix. Both grass and cultivated sites

had various degrees of salinity and water-table depth. Four to five samples, composited into one sample, were taken at a radial distance of about 20 feet from the wells. The table shows monthly values of surface (0 to 6 inches) soil salinity, water-table depths, and total precipitation between reading periods.

A significant correlation occurs between surface soil salinity and water-table depth in the native grass locations. There was no significant correlation of surface soil salinity with water-table depth on the cultivated sites. Other experimental work (*8, 45*) has shown that surface soil salinity was more readily influenced than subsoil salinity by climatic, cropping or cultural conditions.

The prediction equation for evaluating surface soil salinity from water-table depths in the native grass areas is $Y = -2.48X - 22.15$, where X is depth (feet) to water table and Y is surface soil salinity (mmhos/cm). The correlation coefficient was $r = -0.526$.

Ridge-Depression Hydraulic Heads

During the growing season, hydraulic gradients in a saline ridge and adjacent nonsaline depression (fig. 29) indicate that upward flow occurred in the ridge, but flow was downward in the depression. The data (fig. 29) is an average for 1967 and 1968. Growing season precipitation (May 1 to November 1) was about 9 inches below normal (14.8 inches) in 1967

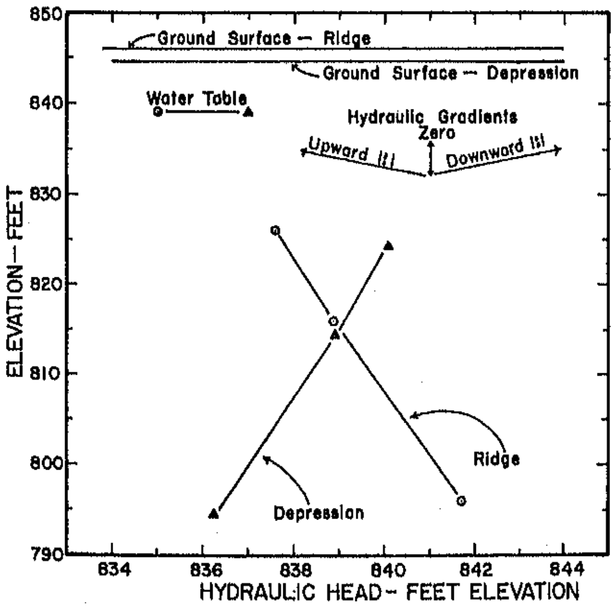


FIGURE 29.—Two-year average hydraulic heads and vertical gradients in a saline ridge and adjacent nonsaline depression. The gradients were upward on the ridges and downward in the depressions.

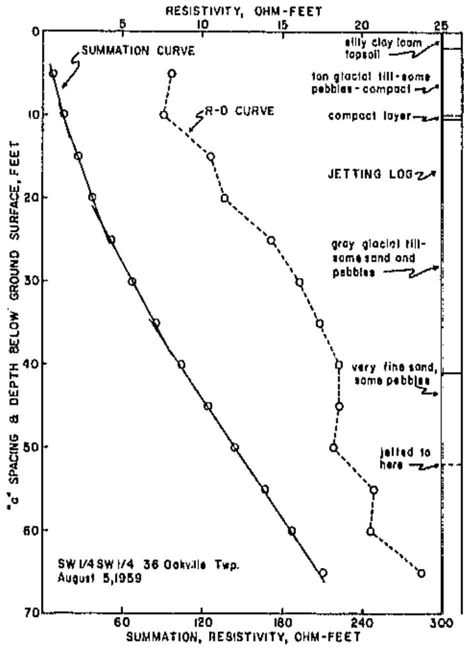


FIGURE 30.—Stratigraphic formation log obtained in a saline area by the electrical resistivity and jetting methods.

but about 4 inches above normal in 1968. Irrespective of this difference in precipitation, gradients and average water tables varied little between the two seasons.

Over a long period, the general trend is that accumulated surface waters (precipitation and snow melt) in the depressions causes downward flow to depths of 20 feet. No surface water accumulates on the ridges; therefore, the vertical hydraulic gradients remain upward. As a result of this differential hydrologic flow, the depressions are nonsaline but the ridges become salt sinks (see Ridge-Depression Ground Water Movement, and references *6* and *40*).

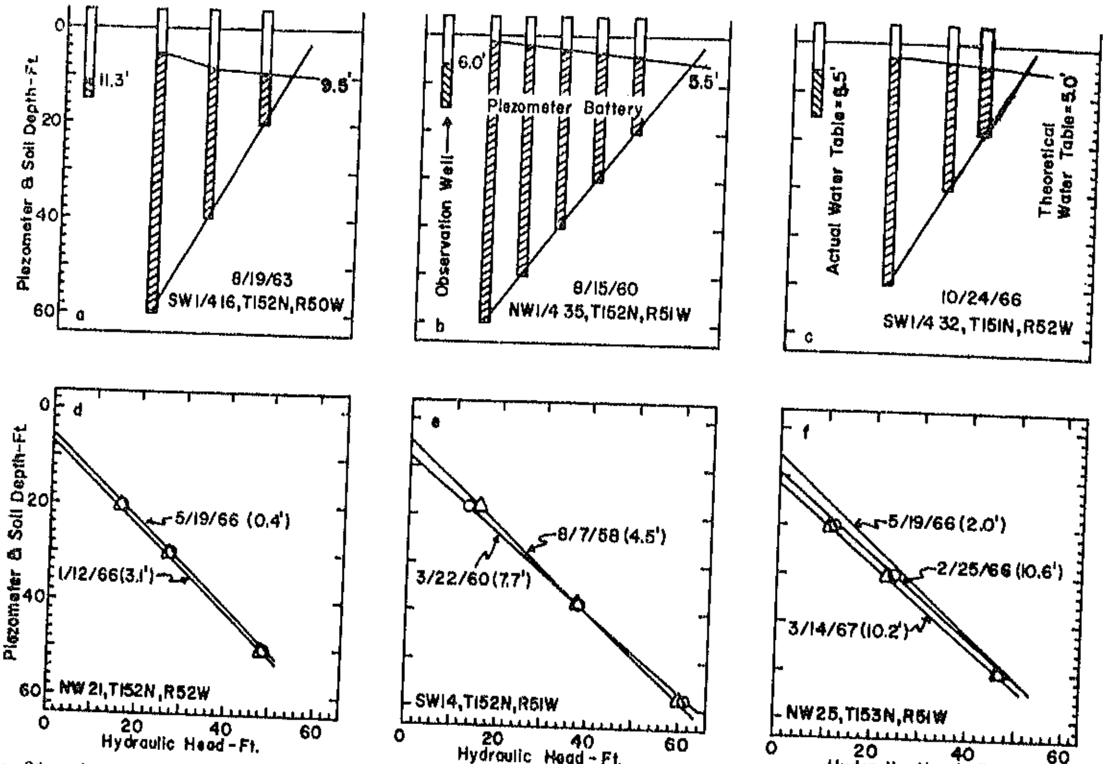


FIGURE 31.—Actual and theoretical (by two methods) water-table depths (feet) at several locations and on several dates.

is possibly due to a compact layer. The slope change at 23 feet cannot be explained, but at 37 feet the material changed from glacial till to sand.

Theoretical Water Tables

A piezometer measures the hydraulic pressure at the desired depth in the soil. The water level in a single piezometer coincides with the water table only if vertical movement in the soil is absent. A piezometer battery (several piezometers terminating at different depths at a location) can be used to estimate the water-table depth at a point in time. Some theoretical water tables and the actual water tables (measured in 15-foot observation wells) on a particular date at six locations are given in figure 31. All of the piezometer batteries except f were located inside the study area (fig. 4). The graphs represent two methods of showing theoretical water-table depths and compare them with actual water tables. Because the water table and water movement in the soil is a dynamic process —affected by precipitation, temperature, solute and other gradients, time, variability in soil hydraulic conductivity and other factors—hydraulic gradients are not always smooth or uniform as shown in figure 31b but can be as indicated in figure 31a. At locations a, b, and c (fig. 31) theoretical water tables (those based on piezometer battery water levels) are higher than actual water tables (those measured in the observation well) on the dates given.

In a, b, and c of figure 31, a zero hydraulic gradient or no vertical flow is indicated when the water levels are the same in all piezometers in a battery. Thus, the top line, connecting piezometer water levels, would be horizontal.

In d, e, and f of figure 31, a zero hydraulic gradient is indicated when the slope of the hydraulic head line is 45 degrees. A slope more than or less than 45 degrees shows there is an upward or downward gradient, respectively. In the figures, straight lines are drawn through all soil measuring points that would indicate a uniform gradient, isotropic soils, and no hydraulic influences, that is, a steady state case. This, however, is rarely true and often upward and downward gradients occur in a soil profile. Assuming the steady state case on each of the several dates shown (15-foot observation well water tables are given in parentheses following the date), the theoretical water table would be at the soil depth where the hydraulic head line cuts through the ordinate. To illustrate the method in Figure 31e, the theoretical water table on August 7, 1958, was 4 feet (actual was 4.5 feet).

SUMMARY

• The salinity problem exists in a dryland-farmed area of the Red River Valley of the North that is identified with high water tables, poor internal and surface drainage, and underlying saline artesian waters.

• Hydrologic and soils information were obtained primarily within a 200-square mile study area, from individual experiments, and from locations outside the study area.

• Ground surface slopes range from 3 ft/mi near the Red River to between 10 and 15 ft/mi at the western edge of the Valley.

• Soils formed on lacustrine deposits near the Red River and on glacial till west of the lacustrine deposits. The lacustrine soils are usually high in silt content. Glacial till is variable in texture but usually contains more sand and clay than lacustrine soils.

• Geologic formations from the ground surface downward consist of (a) recent age alluvium, (b) glacial drift, (c) Cretacous shales and sandstones, (d) Ordovician limestones and (e) Precambrian granite.

• The problem area has many flowing and nonflowing saline artesian wells that provide water for most uses except irrigation and human consumption. The salt sources of the artesian waters are the Cretaceous sandstones and the Ordovician limestones.

A domestic wells survey indicated a relationship between high artesian pressures and soil salinity. Calculated leakage upward from two individual domestic wells indicated that saline water leakage to the soil surface horizons could approach up to 23 in/yr. An over-winter soil-water study indicated this upward leakage to be about 3 in/yr whereas a more recent pump test study shows this leakage is about 0.5 inches annually.

• Artesian well water salinity averaged 8.8 mmhos/cm (about 5,600 p/m) and consisted primarily of sodium, calcium, and magnesium chlorides and sulfates. The pH and boron averaged 8.1 and 3.1 p/m. Sodium was the principal cation followed by calcium and magnesium. Chloride was the principal anion followed by sulfate. SAR averaged 18.

Shallow ground water in observation wells ranged in salinity from 0 to 60 mmhos/cm and was similar in chemistry to the ambient soil. Ground water in the till area had a chemistry similar to that of the artesian well waters, but the lacustrine soil waters were high in magnesium and low in boron, which is probably due to a chemical change occurring in movement of the water through the lacustrine materials.

Ground water in shallow observation wells and 20-foot piezometers in the ridge-depression microrelief area within the saline area, varied from nonsaline in the depressions to highly saline in the ridges. This variation was probably due to increased leaching in the depression as a result of impounded precipitation.

• Water tables in the study area fluctuated between 1 to 15 feet below ground surface. Seasonal trends indicated a high and fluctuating water table during late spring and summer, then showed a receding water table in late summer, fall, and overwinter.

The receding water table overwinter makes artesian leakage upward to the water table appear nonexistent. An overwinter study of the water table, however, showed that ground water was translocated to near-surface soils because of temperature gradients. The amount of translocated water was greater than that accounted for by the water table drop alone; thus, the additional water probably came from the upward leaking artesian waters.

• Surface drains were effective for removing surface water but ineffective with regard to water-table control. Crop growth was poor adjacent to drains.

• In the saline ridge-nonsaline depression microrelief areas, water-table fluctuations were greater and more rapid in the depressions than the ridges. Hydraulic conductivities were much higher in the depressions than in the ridges.

• The type of crop or cultural practice affects water-table depths, fluctuations, and depth and rate of soil freezing. The water table was higher under a bare or mulched soil than it was under a cropped soil.

Diurnal fluctuations of the water table occurred in a tree shelterbelt growing in a depression. Water use by the trees, when using a specific yield of 2 percent, was calculated at approximately 0.12 in/d during a short period.

• Calculated crop water use exceeds precipitation in the area; thus, high-water tables are not due to precipitation.

• Piezometer batteries terminating in materials overlying the saline artesian aquifer showed upward gradients; thus, there exists an upward movement of the artesian water and its dissolved salt load.

• A significant negative correlation existed between surface-soil salinity and water-table depth in native grass areas, but not in diversified cropped areas. High-water table areas had high surface soil salinity.

MANAGING SALINE SOILS

The information obtained from numerous studies and experiments conducted from 1955 to 1970, show the possibility of reducing soil salinity and making the salt-affected soils agriculturally productive.

Three major approaches were used in the studies: (a) understanding the problem; (b) living-with-the-problem types of solution; and (c) long-term types of solutions such as removing or reducing existing and incoming salts from the soil, or reversing or decreasing upward artesian flow gradients and lowering the water table.

Studies in understanding the problem were concurrent with studies to learn how to live with the problem and how to reclaim saline areas for agricultural production. Tile drainage work was directed toward permanent reclamation. These experiments were relatively ineffective because of upward leakage of saline artesian waters, low hydraulic diffusivities, and the lack of depth of the tile drains. Precipitation was the only leaching water available.

With more geological information becoming available, some additional research was directed toward types of permanent reclamation. This work consisted of pumping tests for drainage from the underlying saline artesian aquifer to reduce the piezometric head (a confined aquifer pump test) and from the overburden material (unconfined aquifer pump test).

The studies indicated that contributions of saline ground water into the area from artesian sources could range from 0.5 to 1.0 in/yr (*10, 20*). The salt load deposited in the soil from this upward leakage—assuming the electrical conductivity of the water to be 7 mmhos/cm—would then range from 0.25 to 0.5 tons of salt per acre annually.

Results obtained apply to solution of the drainage and salinity problem and will be discussed in this section. The cited references contain details of particular experiments or studies.

LIVING WITH THE PROBLEM

Crop Response to Leaching and Impounded Precipitation

Objectives of this experiment were to evaluate soil salinity changes, which result from initial leaching plus natural precipitation under cropped conditions, and to evaluate a wheat crop response.

The experimental treatments consisted of:

A. Precipitation only: border dikes on three sides of plots permitting runoff

B. Precipitation impounded

C. Nine inches of nonsaline leaching water plus impounded precipitation

D. Eighteen inches of nonsaline leaching water plus impounded precipitation

Located on a moderately saline ridge, the field plots did not have water-table control and received one application of leaching water. The 4-year study indicated that soluble soil salts could be moved in the soil profile (*45*).

Leaching the soil with either applied water or impounded precipitation, or both, was effective in desalinizing the top 28-inch soil profile (fig. 32) and in increasing crop yields (table 1). Leaching moved the soluble soil salts to depths of 3 feet or more. Without internal drainage, the salts were not permanently removed from the soil profile and thus, were free to move in response to factors affecting soil solution movement.

Measured precipitation during the study was near or above normal during the first 2 years and about 2 inches below normal during the last 2 years. Significantly, the average annual water tables were highest the first 2 years. Growing season water tables did not show the same trend but were influenced more by abnormal monthly precipitation. Water tables fluctuated

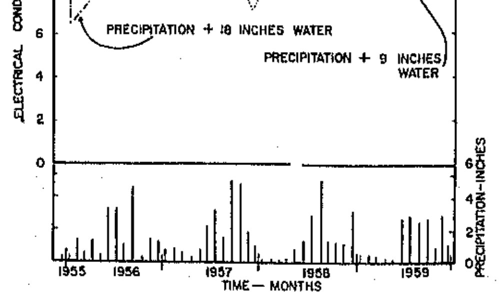


FIGURE 32.—Effects of leaching treatments on soil salinity in the top 28 inches of soil.

Table 1--Wheat yields and test weights, precipitation, and average water tables

	1956		1957		1958		1959		Averages	
Treatment	Yield	Test wt	Yield	Test wt	Yield	Test wt	Yield	Test wt	Yield	Test wt
	Bu/A	*Lb/bu*	*Bu/A*	*Lb/bu*	*Bu/A*	*Lb/bu*	*Lb/bu*	*Bu/A*	*Bu/A*	*Lb/bu*
	- - - - - - - - - - - - - - Crop yields and test weights - - - - - - - - - - - - - -									
A	9.4	50	8.9	46	6.0	56	2.5	48	6.7	50
B	9.8	50	10.8	45	27.5	60	13.3	52	15.3	52
C	12.0	51	11.3	48	28.3	61	13.0	52	16.1	53
D	26.2	54	18.4	50	30.8	60	13.3	53	22.2	54
LSD1/ - 0.5	7.2		5.3		3.3		1.8		3.6	
- 0.01	10.4		7.6		4.7		2.6		5.2	
	- - - - - - - - - - - - - - Precipitation, Inches - - - - - - - - - - - - - -									
									Long term	
Annual	19.4		22.0		17.8		17.4		20.0	
Growing season2/	12.1		12.0		10.6		10.7		12.0	
	- - - - - - - - - - - - - - Water table depth, Feet - - - - - - - - - - - - - -									
Annual	6.7		6.5		7.4		7.9		7.1	
Growing season2/	5.7		8.1		6.0		7.2		6.7	

1/ Least significant difference. 2/ May through August.

from 2 to 12 feet during the period. The wheat-yield-to-soil-salinity correlation coefficient (0.79) was highly significant. The curvilinear regression equation of wheat yields (Y, in bushels per acre) on salinity (EC in mmhos/cm) in the 6- to 16-inch soil depth at planting time was $Y = 68 - 8(\mathrm{EC}) + 0.25(\mathrm{EC})^2$, (*45*).

The soluble sodium content in the top 28 inches of soil was reduced at the end of 4 years in all treatments receiving impounded precipitation plus leaching water. Soil pH did not change during the 4 years. Internal drainage plus precipitation could be effective in reclaiming the saline soils by moving the soluble salts downward out of the root zone. Because adsorbed sodium was also reduced, leaching had no ill effects on soil structure.

Soil Salinity Response to Bare Fallow, Barley, and Grass

The practice of cultivated fallow for water conservation, often used in subhumid and semiarid climates, was effective in reducing soil salinity. A 4-year study compared soil salinity under the continuous three land-use treatments of bare cultivated fallow, barley, and perennial grass (*44*). The experimental site was a saline Glyndon silt to silty clay loam with a shallow and fluctuating (2 to 10 feet), uncontrolled water table. Plots were diked and received only precipitation. During this 4-year study, precipitation was below normal. Piezometer batteries indicated vertical upward flow gradients.

The average soil salinity values from four replicates per treatment, by 6-inch increments, are given in table 2. Soil salinity varied considerably near the surface with grass and barley treatments but was much less variable with fallow.

Average 24-inch soil salinity for the period and monthly totals of precipitation plotted in figure 33 show soil salinity highest in the grass and lowest in the cultivated fallow. Precipitation influenced salinity and water-table depths. During the growing season, water tables were usually higher—sometimes as much as a foot—under the fallow than under the grass (see Agronomic Cultural Effects on the Water Table). Soil-water-suctions during the growing season were high under the grass but indicated that evaporation losses were low for the cultivated fallow.

Results of the analysis of variance relating treatment effects to soil salinity are given in table 3. At all sampling periods (except two summer sampling dates) including the 3-year average, soil salinity in the 0- to 24-inch depth was significantly affected by treatment.

Measured soil chemical changes indicated a removal of chlorides but not sulfates. The pH decreased slightly under cultivated fallow in the 12- to 36-inch increment. Cation removal in decreasing order of magnitude was sodium, magnesium, calcium on a percentage basis. Adsorbed sodium was reduced under cultivated fallow but increased under grass. Cultivated fallow was effective in reducing salinity. At the end of one growing season, salinity decreased about 40 percent in the top 24 inches. In the final year of the four-season experiment, wheat was grown as the test crop because it is less tolerant of salinity than barley and thus a better indicator of salinity. Wheat yields were 16 bushels per acre following 3 years of cultivated fallow as compared to 4 bushels per acre following 3 years of barley.

Table 2--Average soil salinity expressed as electrical conductivity, in 6-inch depth increments under three continuous land use treatments during a 4-year period. Standard deviations are in parenthesis

Treatment	Depth	1960 Spring	1960 Summer	1960 Fall	1961 Spring	1961 Summer	1961 Fall	1962 Spring	1962 Summer	1962 Fall	1963[1/] Spring	1963[1/] Summer	1963[1/] Fall
	Inches	*Millimhos per centimeter*											
Grass	0-6	2	4(3)	5(4)	4(3)	9(8)	3(2)	2(2)	3(2)	5(4)	9(6)	12	9
	6-12	6	10(4)	15(3)	11(5)	17(5)	14(5)	7(5)	6(5)	15(5)	14(5)	16	18
	12-18	12	15(4)	19(1)	18(3)	20(2)	22(1)	16(6)	13(5)	19(2)	18(1)	19	20
	18-24	16	18(3)	18(2)	18(2)	19(2)	20(1)	20(5)	18(4)	18(2)	19(3)	19	18
	Average	9	12	14	13	16	15	11	10	14	15	17	16
Barley	0-6	2	3(3)	4(2)	2(2)	5(4)	2(2)	2(2)	2(2)	3(3)	6(2)	9	6
	6-12	6	6(3)	9(4)	6(3)	9(5)	7(3)	5(2)	5(3)	9(4)	10(4)	12	11
	12-18	10	11(4)	12(5)	10(4)	12(4)	12(4)	10(4)	8(4)	14(4)	14(4)	15	14
	18-24	12	14(4)	13(3)	13(3)	13(4)	12(6)	12(4)	12(3)	13(3)	14(3)	15	13
	Average	7	9	9	8	9	8	7	7	10	11	13	11
Fallow	0-6	2	3(2)	3(1)	3(1)	3(1)	2(1)	2(1)	2(1)	2(2)	3(1)	3	3
	6-12	8	6(1)	5(1)	5(1)	5(2)	5(1)	4(2)	4(1)	4(2)	5(0)	5	5
	12-18	14	8(1)	6(2)	9(1)	7(2)	5(2)	5(2)	5(1)	5(2)	6(1)	7	8
	18-24	15	10(2)	8(2)	13(2)	10(2)	6(4)	6(2)	6(2)	7(2)	7(2)	6	9
	Average	10	7	6	7	6	5	4	4	4	5	5	6

1/ In 1963, the barley and fallow plots were seeded to wheat.

Effects of Fallow, Straw Mulches and Crop Residue

Straw mulch overwinter effects

This study was an overwinter evalution of the water table, soil water and piezometric pressures under two land surface treatments—bare fallow and straw mulch (2.7 tons per acre—straw about 3 inches deep). The water table and related portions of the study were discussed briefly in the section on Artesian Conditions and also by Benz and associates. (*8*).

A summary of soil salinity changes over 3 years is given in table 4. Straw mulch was an effective way to temporarily reduce soil salinity in the plant root zone. Under bare fallow, a soil mulch should be maintained, through cultivation, to induce soil salinity reductions. Reductions in salinity occurred under both treatments, but they were continuous under the straw as compared to the bare soil treatment where changes were erratic —decreasing the first season and increasing slightly in the upper 18 inches the third season.

The considerable increase in salinity in 1962 over 1961 was probably a result of nontillage, which emphasizes the need for a noncompacted, cultivated, or mulched condition. Salinity reductions under straw mulch suggest that wheat yields (see equation in Crop Response to Leaching) could be increased by 10 to 20 bushels per acre, and there is an option for growing crops that are more sensitive to salinity.

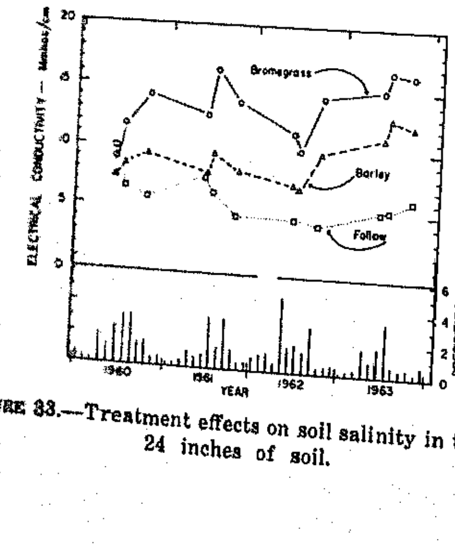


FIGURE 33.—Treatment effects on soil salinity in the top 24 inches of soil.

Land use effects

Summer land use, winter cover, and depth to water table significantly influenced soil salinity (*42*). Experimental work was conducted at two sites to evaluate the effects of fallow and crop residue management on soil salinity at two levels each of soil salinity and water-table influence. Site 1 had a moderate level of salinity and a moderate depth to water table; and Site 2 had high salinity and a high water table.

Table 3--Treatment (fallow, barley, grass) effects on soil salinity, 0-24 inches deep--analysis of variance

Time	F[1/]
3-yr average	12.2**
Jul. 21, 1960	3.6
Sep. 22, 1960	12.1**
May 2, 1961	7.1*
Jul. 5, 1961	15.0**
Oct. 4, 1961	20.5**
May 16, 1962	6.6*
Jun. 26, 1962	4.7
Oct. 2, 1962	37.5**
May 14, 1963	15.2**

1/ Significance: ** = 99% = F > 10.92; * = 95% = F > 5.14.

Table 4--Soil salinity changes over 3 years under bare fallow and straw mulch on fallow. Standard deviations are in parentheses

Treatment	Date	Soil depth - Inches 0-6	6-12	12-24	24-36	36-48	48-60
		- - - - - - - - - - - - *Millimhos per centimeter* - - - - - - - - - - - -					
		Area fallowed during summer 1960--Straw mulch applied in fall 1960					
Straw	11-3-60	6.5(1.3)	8.3(1.2)	14.7(3.6)	28.1(4.2)	34.0(2.3)	34.0(.80)
Do.		Plots cultivated during summer 1961--Second straw mulch applied in fall 1961					
Do.	10-25-61	4.0(.92)	6.1(.47)	9.3(1.6)	20.3(2.6)	30.8(2.8)	32.0(2.4)
Do.	1-11-62 1/	4.1	6.4	8.9	11.3	24.4	31.9
Do.	6-26-62	3.0	4.8	5.8	14.4	32.0	35.0
		Plots not cultivated during summer 1962					
Do.	11-16-62	3.9(1.6)	5.6(1.4)	6.4(.40)	11.2(1.7)	30.1(1.7)	36.7(1.2)
Do.	5-14-63	4.5	5.5	7.5	15.1	30.4	34.8
Do.	7-2-63	4.3	4.7	5.6	11.7	nd 2/	nd
		Plots cultivated during summer 1963					
Do.	10-9-63	3.8(1.0)	4.6(.35)	6.3(.62)	11.9(4.0)	27.6(3.4)	30.3(2.4)
Fallow	11-3-60	6.8(.40)	9.1(.93)	13.1(2.3)	27.6(5.1)	33.0(2.3)	33.0(1.6)
		Plots cultivated during summer 1961					
Do.	10-25-61	5.4(.53)	7.7(.62)	10.5(2.0)	23.2(3.7)	36.3(5.0)	36.7(4.2)
Do.	6-26-62	7.8	9.8	13.6	27.9	38.0	35.0
		Plots not cultivated during summer 1962					
Do.	11-16-62	13.6(1.4)	13.2(1.7)	17.5(2.9)	29.7(5.7)	38.7(5.0)	39.9(4.6)
Do.	5-14-63	9.2	10.8	13.9	27.3	37.6	39.3
Do.	7-2-63	10.1	10.0	13.9	27.1	nd	nd
		Plots cultivated during summer 1963					
Do.	10-9-63	11.5(1.7)	11.5(.93)	17.5(3.2)	32.5(4.7)	38.7(4.7)	35.2(2.0)

1/ Unable to sample fallow plots this date due to frozen soil conditions.

2/ Not determined.

The locations were several miles apart on similar lacustrine soil and on nearly level topography. Five rotation treatments were used in the 1963-67 study (table 5). The winter treatments consisted of bare soil, a stubble-mulch, and small grain straw applied at 1.25 tons per acre. Summer land use was cropping to either barley or spring wheat or fallowing.

The B rotation (table 5) was omitted at Site 2 because of the difficulty in growing a crop. Rotation A was used as the check or control treatment. Forty pounds per acre each of N and P was applied each year on plots seeded to small grain. Summer-fallowed plots were cultivated at least three times during the season to maintain good weed control and a soil mulch. The stubble was fall-cultivated after harvest with a narrow sweep cultivator.

Soil salinity, evaluated by analyzing saturation extracts from five to six test holes per plot, was measured before spring planting and after fall harvest. Water tables and ground water salinity were measured from

Table 5--Rotations for winter covers and summer land use as imposed at two sites that differed in salinity and water table levels

Years 1/	ROTATION TREATMENTS (Winter-Summer land use) A	B 2/	C	D	E
1st	Bare-Crop 3/	Stubble-Crop	Bare-Fallow	Straw-Fallow	Bare-Fallow
2nd	Bare-Crop 3/	Stubble-Crop	Bare-Fallow	Straw-Crop	Bare-Crop
3rd 4/	Bare-Crop 3/	Stubble-Crop	Bare-Crop	Stubble-Crop	Stubble-Fallow
4th	Bare-Crop 3/	Stubble-Crop	Straw-Fallow	Stubble-Fallow	Bare-Fallow

1/ First year was fall 1963 to fall 1964.

2/ Treatment B was omitted at site 2 where soil salinity was high.

3/ The stubble was buried by moldboard plowing after harvest.

4/ The test crop was barley except in the 3rd year when spring wheat was seeded.

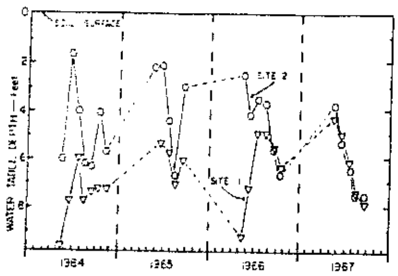


FIGURE 34.—Water-table fluctuations during 3 years at Sites 1 and 2.

three observation wells at each site. Rainfall was also measured at each site during the growing season. Precipitation was near normal in 1964 and 1966 but above normal in 1965 and below normal in 1967. Each year monthly totals deviated greatly from normal.

The water table, measured only during the growing season, ranged in depth from 5 to 10 feet at Site 1 and from 2 to 8 feet at Site 2 (fig. 34). Analyses of the shallow ground water indicated salinity at Site 1 ranged from 26 to 30 mmhos/cm and at Site 2 from 45 to 50 mmhos/cm. At Site 1, soil salinity in the top 24 inches of profile (fig. 35) was reduced the most under Rotation D followed by Rotation C and then B during the 4 years. An increase in salinity occurred in Rotation A; Rotation E remained virtually unchanged. Year-to-year salinity reductions were significant under the straw mulch and fallow treatments, but cropping and bare winter treatments increased or maintained the level of salinity.

At Site 2, the greatest salinity reduction also occurred in Rotation D (fig. 36). At the end of 4 years, salinity in the top 24 inches of soil decreased from 34 to 11 mmhos/cm. Some reduction also occurred in Rotation C. Salinity in Rotations A and E ended up at about the same level as in the beginning, but reductions up to 10 mmhos/cm occurred during intervening years.

Surface vegetative mulches during the winter and summer fallow during the growing season reduced soil salinity; cropping, however, increased salinity. For

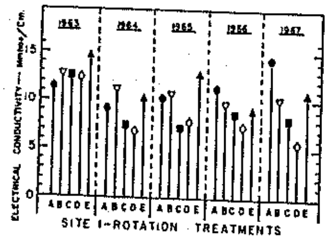


FIGURE 35.—Treatment effects on soil salinity (0 to 24 inches) at Site 1.

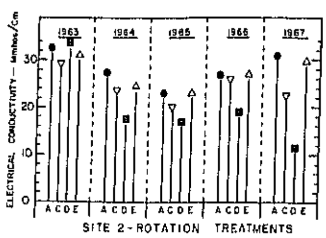


FIGURE 36.—Treatment effects on soil salinity (0 to 24 inches) at Site 2.

example, Site 1 showed a net average soil salinity (EC) reduction of 2.5 mmhos/cm in the 6- to 12-inch depth from summer fallowing but an increase of 2.9 mmhos/cm when cropped. The combination of straw cover over winter plus summer fallow produced large reductions in soil salinity at both sites.

Summer fallow reduced soil salinity more effectively at the moderately saline site (Site 1) than at the highly saline location (Site 2). Compared to bare soil during the winter, straw or stubble reduced salinity. Applied straw was more effective in reducing salinity near the soil surface at the highly saline site, but stubble mulch was slightly more effective than applied straw at the moderately saline site.

Climate also influenced the salinity regime, particularly the times and amounts of precipitation. During dry periods, salinity increased in the cropping treatment but remained mostly static in the fallow treatment; during wet periods, salinity decreases were high under the fallow treatment but only slight under the cropped plots. The fall application of straw mulch increased leaching efficiency during wet periods.

In 1966 crop yield (table 6) comparisons among treatments were best when four of the five rotation treatments were planted to spring wheat. Wheat is a better indicator crop because it is more sensitive to soil salinity than barley. Rotations A and B produced lower yields than Rotations C and D at Site 1. At Site 2, because of previous straw treatment, only Rotation D had a sufficient salinity reduction to produce a crop.

Table 6--Crop yields at the two locations during the 4 years of study

Year-Crop	ROTATION TREATMENT A	B	C	D	E
	- - - - - - -	- -Bushels	per acre -	- - - - -	- - -
			SITE 1 (moderate)		
1964-Barley	1/ 102	1/ 88	2/	2/	2/
1965-Barley	49	55	2/	54	39
1966-Wheat	21	27	34	54	2/
1967-Barley	50	47	2/	2/	2/
			SITE 2 (Severe)		
1964-Barley	0	-	2/	2/	2/
1965-Barley	1	-	2/	18	1
1966-Wheat	0	-	0	14	2/
1967-Barley	0	-	2/	2/	2/

1/ Yield includes grain + straw in 1964.

2/ Plots in summer fallow.

Cultural practices that promote soil water conservation can reduce and control soil salinity under dryland conditions.

Soil salinity changes were significantly influenced by summer land use, winter cover, and depth to the water table. Cultivated summer fallow reduced salinity in the root zone; the greatest reductions occurred under the deeper average water table at the moderately saline site. Salinity increased under a small grain crop. More effective at the highly saline, high water-table site, was an applied straw mulch or overwinter standing stubble mulch that further reduced salinity. The straw mulch was not as effective at the moderately saline, low water-table site. Use of an overwinter straw mulch and a cultivated summer fallow proved the most effective treatment for reducing soil salinity in the root zone.

Soil Salinity Reductions by Fallow or Crop and Different Winter Covers

As in the previous experiment, applying an overwinter cover of straw followed by summer fallow was effective in reducing soil salinity. Summer fallow and either a bare or straw cover overwinter almost tripled the yield of wheat compared with a bare overwinter and summer-cropped treatment (*41*).

More conclusive information on cultivated fallow and vegetative mulches was obtained from a randomized block 4 by 2 factorial design field experiment consisting of four types of winter cover and two summer land-use treatments.

Winter Cover	*Summer Land Use*
1. Bare (check)	1. Barley crop (check)
2. Barley winter cover crop	2. Summer fallow
3. Flax winter cover crop	
4. Straw mulch cover (applied)	

The above treatments were imposed for the first 2 years but on the third year (1970), a common crop of hard red spring wheat was grown on all of the plots. Because it is more sensitive to salinity than barley, wheat was used as the indicator crop. Objectives of this experiment were to evalute the influence of four winter cover treatments in combination with two summer land use treatments: (a) salt movement in saline soils and (b) crop yields. Data obtained included soil profile salinity (spring and fall), crop yields, amount of winter cover, soil temperatures, soil water, soil water tension, artesian pressure, water-table depth, and precipitation.

The study site was located on nearly level saline Glyndon silt loam. Average soil salinity ranged from 12 mmhos/cm in the surface foot to 25 mmhos/cm at the 12-foot depth. Sufficient fertilizer was applied before spring seeding and before seeding the winter cover crop in the fall to avoid yield and growth differences due to fertility. The straw mulch was applied at a rate of 3,000 pounds per acre.

Average precipitation was below normal in 1969 and 1970 but slightly above normal in 1968 (table 7). Water tables in the experimental area averaged 6.5 feet and ranged from 3.3- to 13-foot depths following the normal seasonal pattern (fig. 13). Salinity, primarily magnesium and sodium chlorides, ranged between 42 to 49 mmhos/cm. Ground-water salinity was usually higher in the fall than in the spring, but the level of salinity never exceeded 49 mmhos/cm.

Piezometer data indicated upward flow gradients. Pressures in the 40- and 60-foot piezometers remained nearly constant during the 3 years, but the pressure in the 20-foot unit fluctuated considerably.

Soil temperature gradients were downward during the summer and upward during the winter under all treatments. There were differences, however, in temperatures and in ranges of temperature because of treatment differences. The average January temperature at the 8-inch depth was about 5° F warmer under straw cover compared to bare soil. Temperature differences plus the accompanying differences in gradients acted as driving forces in the movement of soil water.

Soil water tension was usually low under the fallow treatment. Soil water content was substantially greater under straw as compared with bare soil.

A comparison of bare soil versus straw winter treatments showed that from October 1967 to April 1968 soil water content in the top 36 inches of soil profile was about 15 percent higher under the straw treatment. Seasonal hydraulic head (tensiometer) data comparing cropping vs. summer fallow averaged about one-fourth to one-half as high in the fallow as under the cropped.

Treatments (winter cover:summer land use) for reducing salinity in May 1970 were straw:fallow > bare:fallow > straw:crop > barley:fallow > flax:crop

Table 7--Precipitation during the winter cover and summer fallow or cropping experiment

	Precipitation - Inches			
Month[1/]	Long-term	1968	1969	1970
January-April	3.3	3.9	2.9	2.8
May	2.3	1.5	1.9	3.5
June	3.5	5.5	4.6	2.3
July	3.0	3.9	2.0	2.0
August	3.2	3.0	1.2	1.1
September	1.8	1.8	2.4	3.1
October-December	2.9	1.3	1.9	2.8
Total Annual	20.1	20.9	16.9	17.7

[1/] Winter data are from U.S. Weather Bureau and summer data was collected at the experiment site.

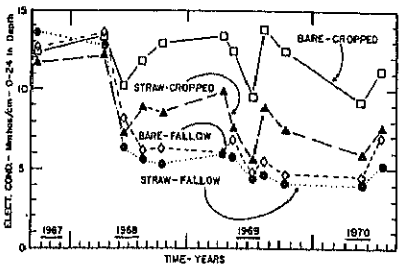


FIGURE 37.—The effects of winter cover and summer land use on salinity of the 0- to 24-inch soil depth.

> flax:fallow > barley:crop > bare:crop (fig. 37). These treatments also gave the most effective cultural-land use combination for reducing soil salinity during the 3 years of the experiment. Four of the eight treatments not shown in figure 37 lie between the treatments bare:cropped and straw:cropped.

The order of treatments for 1970 wheat yields (table 8) were similar to those for reducing soil salinity. Wheat yields in decreasing treatment order were straw:fallow; bare:fallow; flax:fallow; barley:fallow; straw:crop; flax:crop; barley:crop; and bare:crop. Wheat yields ranged from 12.2 bushels per acre for the check treatment to 35.2 bushels per acre when straw mulch was used with fallow. An economic analysis was not performed, but the data indicate that the most preferred treatment combination over a long time would be the winter straw cover, summer cropping, and then at periodic intervals, a summer treatment of cultivated fallow. The correlation between wheat yields and soil salinity was signficant (fig. 38). The regression equation of wheat yields on soil salinity was $Y=24.3-1.5(EC)$, where Y is predicted wheat yields in hundredweights per acre and EC, soil salinity in mmhos/cm in the 6- to 24-inch soil depth.

Effects of Plastic Covers on Soil Salinity Reductions and Sugarbeet Yields

Black plastic film covering about 85 percent of minor soil ridges between rows increased sugarbeet yields. Compared with the conventional planting

Table 8.--Wheat grain yield data for two summer-land-use and four winter-cover treatments

Treatment	Test weights	Grain yield	Control comparison
	Bu/bu	*Bu/acre*	*Percent*
	Summer cropped 1968-69		
Bare (check)	53.4	12.2	0
Barley	54.1	15.4	29
Flax	54.4	15.6	30
Straw	55.0	23.3	95
	Summer fallowed 1968-69		
Bare	54.9	33.8	180
Barley	54.1	24.6	103
Flax	54.9	24.6	104
Straw	55.0	35.2	193

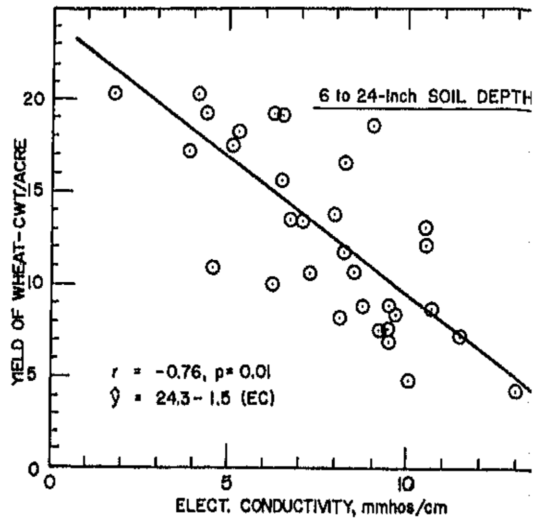


FIGURE 38.—The correlation and regression of yields on salinity (EC) of the 0- to 24-inch soil d

method, soil salinity also was reduced significan clear plastic germination cap over the seed row u hastened emergence by 1 to 4 days (9).

The field experiment, which compared black p film placed between rows and clear plastic film p over rows of minor soil surface ridges, consist duplicate treatments on a saline ridge and an cent nonsaline depression (150 feet apart). Obje in the experiment were (a) improving seed gerr tion and hastening emergence, (b) concentrating cipitation into the crop row, (c) reducing evapor between rows, and (d) increasing soil temperatu

Sugarbeets, a fairly salt-tolerant crop, are sen to soil salinity during the germination, sprouting emergence stages. When grown on saline soils, beets often do not emerge on the ridges. In the saline depressions, however, sugarbeets grow wel

Potatoes, a high value cash crop grown exten in the area, are much less salt tolerant. Potatoe grown only in those areas where soil salinity is lc moderate. Finding and using methods to reduce salinity would make more land available for the duction of high value, salt-sensitive cash crops.

The following treatments on each plot conti for 3 years:

(A) 8-inch soil ridge, no plastic between rows, 4-inch clear plastic germination cap ove rows.
(B) 8-inch soil ridge, with black plastic bet rows (85% coverage) with clear plastic g nation cap over the rows.
(C) Flat (no soil ridge), no plastic, check treat
(D) 8-inch soil ridge, no plastic.

The soil at both sites was a Glyndon silty clay loam, and elevation differed 1.5 feet between the ridge top (saline site) and bottom of the depression (nonsaline site).

Measurements included precipitation, soil temperature, soil water, soil salinity, water-table depth, soil water pressure, sugarbeet yields, and sugarbeet chemical analyses.

During the first and last year, mean growing season precipitation was above normal but much below normal in 1967. During the 3 years water-table depths ranged from 2 to 14 feet. Average water tables in the depression were higher, but seasonal hydrographs of the water table for both sites were similar. On the average, ground water flow was upward in the ridge but downward in the depression as discussed in Ridge-Depression Hydraulic Heads.

During the first and last year, mean growing season precipitation was above normal in 1967. During the 3 years, water-table depths ranged from 2 to 14 feet. Average water tables in the depression were higher, but seasonal hydrographs of the water table for both sites were similar. Vertical ground water flow averaged upward in the ridge but downward in the depression (Ridge-Depression Hydraulic Heads).

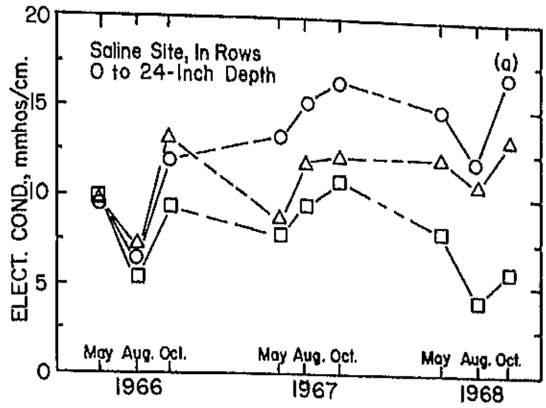
Soil salinity in the 0- to 24-inch soil depth was significantly reduced by the soil ridge treatment and by the use of plastic over the ridge. (fig. 39a). Salinity decreased from spring to summer in 1966 and in 1968 because of above normal precipitation and increased in 1967 because of below normal precipitation. Usually salinity increased from spring to fall irrespective of treatment. Salinity was lowest and varied the least in treatment B during any one year and throughout the 3 years.

In the nonsaline plots, soil salinity was low, but the C treatment became more saline (fig. 39b). Although soil salinity was expected to be higher in the minor ridges (between rows) of treatments A and B, salinity between rows and in rows was similar regardless of treatment.

The slight salinity increase in the 2- to 4-foot soil depth in treatments A and B indicated that salts moved downward from the surface 2-foot depth. The order of treatment effects, from best to poorest, was B, A, D, and C for reducing salinity in the saline and nonsaline sites.

Soil water content, usually higher at the nonsaline site than at the ridge site, showed no definite differences because of treatment or location such as between-row versus in-row.

Soil temperatures were quite similar at the saline



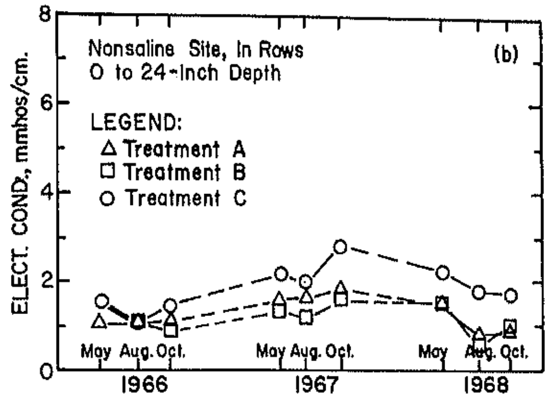


FIGURE 39.—Electrical conductivity of soil saturation extracts taken from soils in the sugarbeet rows at (a) saline site and (b) nonsaline site.

and nonsaline sites. Soil temperature increased with the black plastic between rows and the clear plastic germination cap. Temperatures in the B treatment (0- to 12-inch soil depth) ranged several degrees higher than in the A and C treatments during germination and emergence and remained higher throughout the season. The clear plastic germination cap hastened germination and emergence by 3 to 4 days in treatment B and by 2 days in treatment A compared with treatments C and D.

Treatment at the saline site in 1967 and 1968 and at the nonsaline site in 1967 (table 9) showed a significant difference in sugarbeet production. By comparison, Grand Forks County averages for the 3 years were 1966, 13.1 T/A; 1967, 11.5 T/A; and 1968, 12.7 T/A.[7]

In the saline and nonsaline sites, treatment B usually outyielded the other treatments. The low yield in 1968 in the nonsaline site was possibly caused by exception-

[7]Private communication from J. R. Price, N. Dak. Crop & Livestock statistician.

Table 9--Yields of sugar beets and percentage sucrose

Treatment	Yield--tons per acre 1966	1967	1968	Mean	Sucrose--percentage 1966	1967	1968	Mean
				Saline site (ridge)				
A	12.4	4/ 5.5b	9.9a	9.3	19.1	17.2b	16.9	17.7
B	15.3	8.9c	12.4b	12.2	17.7	17.6b	16.3	17.2
C	13.8	5.5b	12.0b	10.4	18.7	17.7b	17.4	17.9
D	13.2	3.6a	10.7ab	9.2	19.0	16.2a	16.7	17.3
$S\bar{x}$ 1/	0.76	0.43	0.49		0.52	0.26	0.41	
CV-% 2/	9.57	12.5	7.56		4.83	2.54	4.20	
Significance 3/	NS	.01	.05		NS	.05	NS	
				Nonsaline site (depression)				
A	16.2	12.3a	16.1	14.9	16.4	16.5	15.1	16.0
B	16.3	15.4b	14.9	15.5	16.5	16.9	15.0	16.1
C	15.5	12.3a	16.1	14.6	16.2	16.8	14.9	16.0
D	15.0	10.4a	15.2	13.5	16.3	17.1	15.8	16.4
$S\bar{x}$ 1/	0.65	0.62	0.73		0.21	0.23	0.48	
CV-% 2/	7.15	8.41	2.57		2.20	2.38	5.38	
Significance 3/	NS	.01	NS		NS	NS	NS	

1/ Standard deviation.

2/ Coefficient of variation.

3/ Significance at .01 or .05 levels or not significant (NS).

4/ Values followed by the same letter are not significantly different.

ally wet conditions and aeration problems or a P or N deficiency.

The saline site usually had higher sucrose percentages than the nonsaline site. Although there appeared to be little treatment effect within a site, differences occurred between years. Sodium content in sugarbeets was usually higher from the saline than the nonsaline site and was higher in 1967 than in 1968. Treatments A and B had lower sugarbeet sodium than other treatments in the saline site. Potassium in sugarbeets was higher in 1968 than in 1967 and was usually higher from the saline site. Again, treatments A and B had lower potassium than other treatments in the saline site. Amino-N concentration in sugarbeets was higher in 1967 than in 1968 and it was usually greater at the saline site. The percentage of chlorides in sugarbeets in 1966 was high from the saline site; in 1968, chlorides were lower than in 1966 but still slightly higher in the saline site. Treatment at either site caused no difference in chloride content.

The impurity index, a calculated value,

$$I = \frac{3.5\ (\text{Na}) + 2.5\ (\text{K}) + 9.5\ (\text{Amino-N})}{\text{percent sucrose}}$$

generally met the requirements of 300 to 800 p/m. Thus, sugarbeet quality was adequate and good for processing. Treatments had little influence on impurity index.

Conclusions: Soil salinity was reduced significantly through use of black plastic on minor soil ridges between rows compared with the conventional flat planting method. Salinity reductions were probably caused by reduced evaporation and concentration of precipitation in the root zone. Sugarbeet yield increased significantly particularly in years of subnormal rainfall. Increased yields were attributed to greater water conservation and storage for use in critical growth periods, concentration of water in the plant row, reduced evaporation, and increased soil temperature.

A clear plastic germination cap usually hastened emergence by 1 to 4 days, and combined with the black plastic between-rows treatment, increased growth and yields. However, the plastic covers are still too expensive to be economical unless they can be reused or left in place and costs prorated for several years.

DRAINAGE FOR WATER-TABLE AND SALINITY CONTROL

Two approaches were used in permanent-type solutions to the salinity and drainage problem: (a) surface and shallow subsurface drainage and (b) deep pump drainage. Both dealt with drainage for salinity and water-table control. Types of drainage were surface and subsurface consisting of pipe (tile) and pumping.

Tile and Surface Drainage Effects on Soil Salinity and Water Tables

Shallow plastic drains, tile drains, and surface drainage were evaluated under field conditions. The plastic drains were formed from a flat strip of plastic into an overlap circular lining for a cavity constructed by a combination mole plow and tile-laying machine as it was pulled through the field. The drains were installed to a maximum depth of 30 inches. The water table rose above the drain lines only occasionally so the system was ineffective for either internal drainage or salinity control and no data are presented.

Clay tile drains, 6 inches in diameter, were placed at a depth of 5.5 feet in combination with land-forming in an area of minor ridge-depression topography. The ridges were saline but the depressions were nonsaline. The experiment site consisted of four 5-acre treated plots: (1) not graded plus tile drainage, (2) land-leveled plus tile drainage, (3) land-graded, and (4) check—not leveled or graded. Soil sampling sites and observation wells were located on three east-west transects 200 feet apart.

A combination plan-view, a ground surface elevation view, and water-table hydrographs are shown in figure 40. The tile drain influenced water tables when the water tables were high enough. Too often, however, the water tables were below the tile drain. Flow from the drain was only intermittent and dependent on precipitation and land treatment.

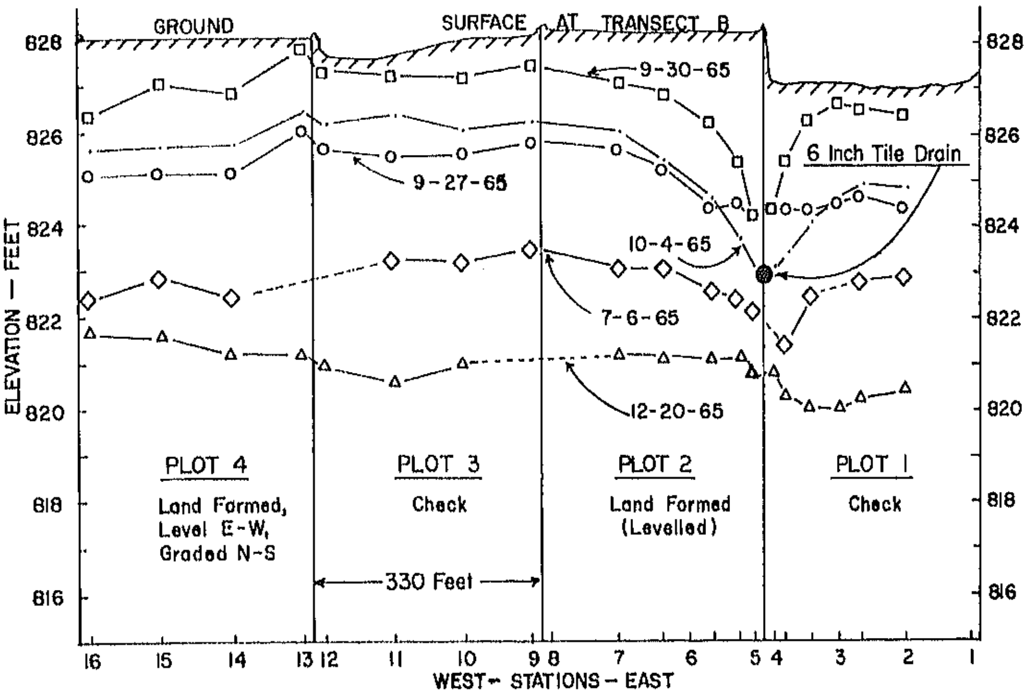


FIGURE 40.—A combination plan view and ground surface elevation view of the tile drainage and land-formed 20-acre area. Water-table depths are shown on five dates.

In 1965, September precipitation was three times the normal 1.9 inches and caused a considerable rise in the water table. From September 18 to 28, the sump pump was being repaired and therefore no tile effluent was removed from the sump. The pump was reinstalled on September 28, and by October 4 the water table developed as shown. Drawdown curves (fig. 40) show that the zone of influence extended to more than 300 feet from the drain. The July and December water tables are shown to illustrate usual levels of the water table.

Soil salinity (plot averages, 0- to 24-inch depth) at the beginning of the experiment and on three later dates is shown in figure 41. The data indicate tile drainage was probably reducing soil salinity adjacent to the drain; however, soil salinity fluctuated in response to the combination of culture (cropping or cultivation) and precipitation. The tile drain was not deep enough to provide continuous drainage.

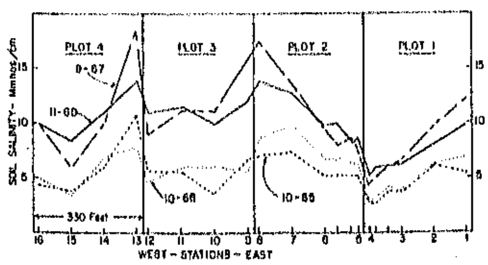


FIGURE 41.—Changes in salinity (electrical conductivity) of the 0- to 24-inch soil depth at four dates during 8 years, as influenced by tile drainage and landforming.

A piezometer battery on the experimental site indicated upward flow. When the artesian flow or artesian contribution is assumed to be 1 inch per year [the actual contribution may vary from 0 to 3 inches (*10, 20*)], the quantity of salts contributed by this water (using EC=7.0 mmhos/cm) is 0.5 ton per acre per year. The total salt outflow in the tile effluent was about 0.3 ton annually. But because that 0.3 tons of salt came from a 5- to 10-acre area adjacent to the drain, the actual salt outflow was only about 0.06 ton per acre per year. Thus, these drains were ineffective for salinity control.

Deeper placement of drains should increase the drain effectiveness somewhat, but deep surface drains have not been effective in providing water-table control and thus reducing soil salinity (see Effects of Surface Drains). Numerous deep (20- to 25-foot) legal drains in the saline areas show no reduction in soil salinity, and some of these drains are 20 to 30 years old.

Pump Drainage for Water-Table and Salinity Control

Two pump drainage systems for water-table control and amelioration of salt-affected soils were studied.

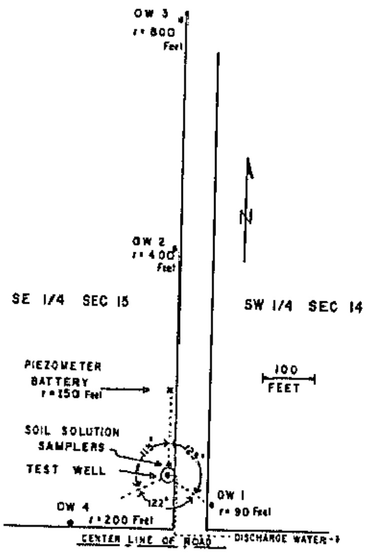


FIGURE 42.—Layout sketch of the pump drainage experiment at the deep test well site.

Objectives of studying the pump drainage systems were to investigate the effect of shallow and deep drainage wells on the water table, evaluate the potential of using pumped wells as sinks for saline ground water to establish a favorable salt balance, and to evaluate the possibility of water-table control and subsequent salinity control in the entire saline area by manipulating the artesian pressure in the underlying artesian aquifer.

Two long-term pump tests were conducted: one on a well that fully penetrated the artesian aquifer (deep-well) and the second on a well that partially penetrated the soil (or overburden) above the artesian aquifer (shallow well). Both pump test sites were within the highly saline and high-water-table area. The deep well test site is located 4 miles north and 5 miles west of Grand Forks (SE¼ sec. 15, T. 152 N. R. 51, W.) The shallow well test site is 1 mile north and ½ mile east of the deep well test site.

Deep well pump test (artesian aquifer)

A test well (to-be-pumped well) and four observation wells were constructed in 1965 and 1966 (locations shown in fig. 42.). Piezometer batteries and soil solution samplers were also installed at the test-well experiment site. The drilling and electric logs showed that the formations, from ground surface downward, were 75 feet of lacustrine materials (silts and clays), 36 feet of glacial till, and 63 feet of sand (Dakota Sandstone or a subcrop of Dakota Sandstone). Thus, the depth from ground surface to the top of the artesian formation was 111 feet.

All of the wells were constructed with forward rotary drilling equipment. The test well fully penetrated the sandstone aquifer, was gravel-packed, and had 50 feet of 10-inch diameter stainless steel screen. Through the overburden, the well casing was 16 inches in diameter and cemented (with concrete slurry) into a 20-inch drilled hole.

The observation wells, for aquifer drawdown measurements, were 2 inches in diameter and gravel packed with a 3-foot length of screen centered in the sand aquifer at the bottom. These casings were also cemented into the overburden to prevent leakage to the ground surface from the artesian aquifer. All the wells were developed by high-pressure water jetting and air injection. None of these observation wells were more than 800 feet from the test well. However, additional wells, including one installed by the Agricultural Research Service and several privately owned farm wells (all artesian but not all flowing), were located at distances of several miles from the test well. All were monitored to evaluate drawdown as influenced by pumping from the deep test well. The casings of many of these domestic wells were in poor condition, but all wells responded during the pumping tests.

Soil samples in 1-foot increments to a depth of 7 feet at 100-foot stations northwest and northeast of the well were taken twice yearly to determine changes in soil salinity. No changes were noted, however, because of the slow response time of the overburden and because the pump test did not last long enough to cause a water-table change.

Piezometer batteries were installed at various depths into the overburden and at several horizontal distances and directions from the test wells. These readings were used to evaluate response in the overburden to pumping from the aquifer. Some of the ⅜-inch diameter pipe piezometers, installed in a drilled hole, had porous ceramic tips on the lower end. They were capped and attached to mercury manometers which made each piezometer a closed system.

Because positive and negative pressures were to be measured, using closed system piezometers should have been the best measurement system.. However, a gas (probably of electrolytic rather than biological origin) formed inside the galvanized pipe causing erroneous manometer readings. Therefore, additional batteries of piezometers (as described in Methods and Materials) were installed by jetting. These were functional, accurate, and read directly by measuring the water levels in pipes.

Soil solution samples were obtained periodically from a site near the pump well to evaluate possible changes in chemistry of the profile.

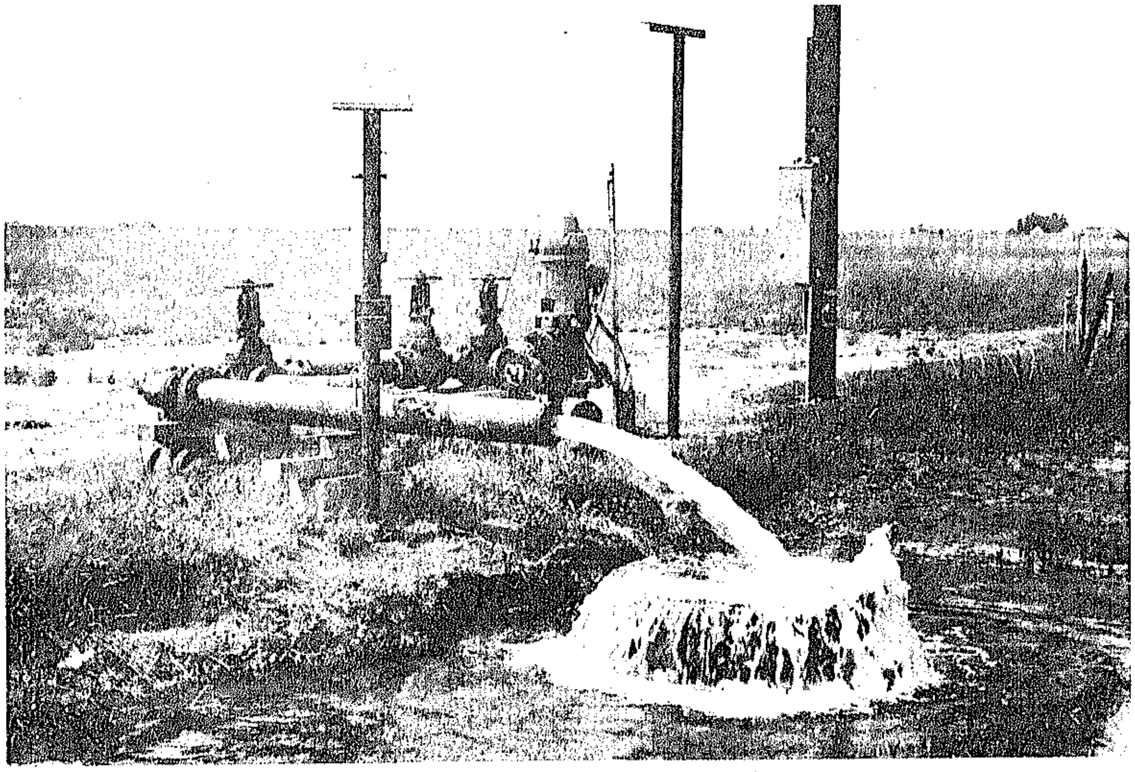


FIGURE 43.—Pumping test in operation.

Pumping tests (fig. 43) were conducted three times: a 24-hour test at 800 gal/min immediately after construction of the well in September 1966; an 18-day test at 500 gal/min in October 1967; and a 179-day test, continuous except for seven brief power outages, at 500 gal/min between June 7 and December 3, 1968.

A longer term pumping test would have been desirous because of the slow hydraulic readjustment in the overburden. However, a longer test would have imposed additional hardship on the surrounding rural people because of water pressure reduction in or flow stoppage from their artesian wells. A longer test would also have required extensive precautions against winter conditions. So to evaluate overburden response to pressure changes resulting from the aquifer pumping, a theoretical approach (*4*) was used.

Discharge of the pump was manually regulated with a gate valve and continuously monitored with a bell-mouth orifice equipped with a standpipe and water-stage recorder. The orifice and recorder were calibrated with an inline flow meter. Data from the four constructed observation wells and continuous readings of atmospheric pressure obtained near the pump site were used to determine the barometric efficiency of the aquifer, which was found to be 26 percent. In other words, a barometric pressure change of 100 millimeters causes a change of 26 millimeters in the water level in a well tapping that aquifer.

Although the water table in the overburden fluctuated considerably throughout the year, a depth of 10 feet below ground surface was used in the analyses. Static piezometric head in the aquifer was about 6 feet above ground surface.

Aquifer transmissibility and coefficient of storage were calculated from drawdown data obtained from the observation wells and test well and by the use of the established nonequilibrium formulas for well tests (*23*). These values are transmissibility (T) of 45,000 gal/d/ft and storage coefficient (S) of 2.2×10^{-4}. The specific capacity of the pumped well was 16.9 gal/min/ft of drawdown after 24 hours and decreased to 10.5 gal/min/ft of drawdown after 179 days of pumping.

Drawdowns in the test well and in an observation well 800 feet away at the end of the 179-day test were 47.2 and 19.5 feet, respectively. Before pumping began on June 7, water levels in the same two wells were about 6 feet above ground surface. At the end of the 179-day test, many farm wells near the test well were no longer flowing, had a greatly reduced piezometric head or both. For example (fig. 44), a well 2½ miles north of the test well had a piezometric head

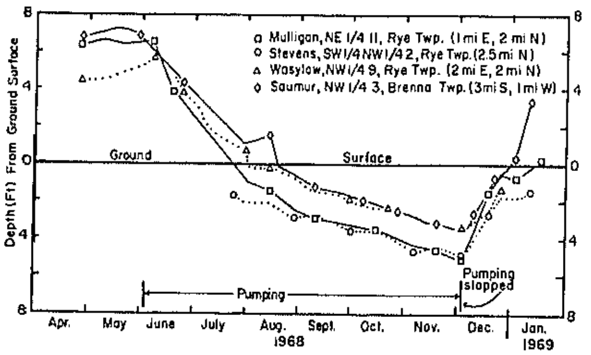


FIGURE 44.—Hydrographs of domestic wells as influenced by the deep well pump test.

reduction of more than 10 feet. The radial distance influenced by pumping exceeded 5 miles. Thus it was evident that enough water could be removed by pumping from the aquifer to reduce the artesian pressure sufficiently so that water-table control could be achieved. The ultimate objective, however, is not to dewater the aquifer but only to reduce the artesian pressure. Reducing the artesian pressure in the aquifer will cause the water table to be reestablished at a greater depth in the soil profile. As a result, salts will leach out of the plant rooting zone and remain at deeper depths.

Overburden permeability, based on an arbitrary selection of a leaky type curve in the pump test analysis, was 58 in/yr. With an average upward hydraulic gradient of 0.16 feet per foot, the amount of water flowing upward to the water table was 9 in/yr.

In a year-round ground water disposition study (*10*), conducted some years previous to the pump test, the artesian flow (through vertical upward leakage) to the water table amounted to about 3.6 in/yr. A water-balance analysis based on the aquifer transmissibility of 45,000 gal/d/ft, an eastward hydraulic gradient of 5 ft/mi in the aquifer, and the surface area affected by excess soil salinity showed that the upward flow contribution of saline artesian water to the water table was about 0.5 in/yr. This flow rate was also shown to be compatible with salt balance calculations for the overburden and is considered a more realistic estimate of the actual amount of leakage. Based on this upward flow of about 0.5 in/yr, the vertical permeability of the overburden becomes 0.01 in/d, which is a reasonable estimate for these fine-textured overburden materials (*20*).

To obtain water-table control by pumping from an artesian aquifer, two conditions must be satified. First, the physical properties of the aquifer must be such that pumping will reduce hydrostatic pressure enough that the water table will be reestablished at a lower depth. Secondly, physical properties of the overburden must be such that water-table control can be effected in a reasonable length of time after reducing the aquifer artesian pressure.

The deep well pump test indicated the economic feasibility of stopping the upward flow of saline water from the aquifer into the overburden. Thus the physical properties of the aquifer are such that pumping can reduce the artesian pressure in the aquifer enough to reestablish the water table at a lower depth.

Piezometer readings, obtained during the 179-day pump test, indicated that the hydraulic pressure redistribution (or reduction) in the overburden was progressing upward but at a rate of only 0.2 ft/d. Hydrographs of three piezometers located 150 feet from the pumped well showed the earliest and greatest response at those depths in the overburden nearest the aquifer (fig. 45). No head reductions were apparent above 60 feet below ground surface (or 50 feet above the aquifer) during the 179-day test.

Hydraulic diffusivities were evaluated from the piezometer data (*4*). Hydraulic diffusivity is the conductivity of the saturated medium when the unit volume of water moving is that involved in changing the head a unit amount in a unit volume of medium (*32*). Low hydraulic diffusivity values are associated with fine-textured materials and indicate a slow rate of growth for pressure responses.

The water flow in this hydraulic system was considered similar to the one-dimensional flow of heat in a semi-infinite slab (*15*) with the hydraulic head being comparable to the temperature. The soil above

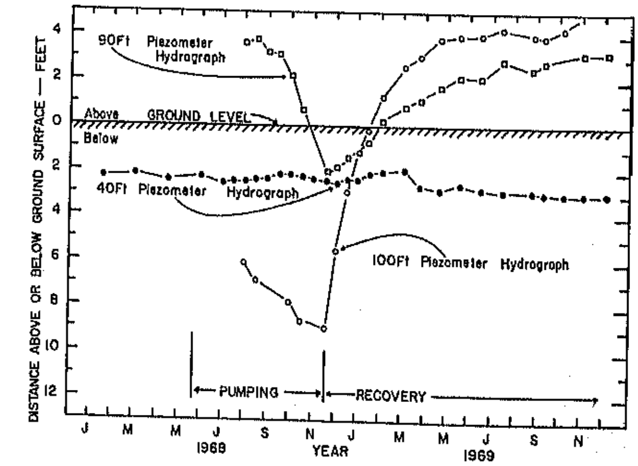


FIGURE 45.—Hydrographs of three piezometers in the overburden located 150 feet from the deep well pump test.

the water table functions hydraulically in the same way an insulative blanket functions relative to heat flow. The aquifer-overburden interface is analogous to the slab surface to which the temperature condition (change) is applied.

The first step in the analysis used the piezometer data obtained from various depths in the overburden (fig. 45) to calculate the hydraulic diffusivity of the overburden materials. Calculated hydraulic diffusivities for the lower 40 feet of the overburden ranged from 0.4 ft^2/d to 2.5 ft^2/d and averaged 1.44 ft^2/d The second step involved applying specific boundary and initial conditions with the previously determined hydraulic diffusivity values and solving the differential equation to evaluate water-table drawdown as a function of time.

The growth of pressure reduction response with time through the overburden was of interest, but the water-table response was of primary importance in this drainage analysis. The effect of hydraulic diffusivity on the time required to effect a water-table response is shown graphically in figure 46. A decrease in hydraulic diffusivity from 2.5 ft^2/d to 0.4 ft^2/d increases the time required for water-table response to begin from 850 days to 1,520 days.

Several examples illustrate use of the curves. Based on the curve for D_o (hydraulic diffusivity) = 1.44 ft^2/d and a water-table drawdown (v) of —5 feet (this would be 5 feet below the existing water table of 10 feet below ground surface), 2,600 days (7.1 years) would be required to produce 5 feet of water-table drawdown when the aquifer drawdown is 32 feet. Or

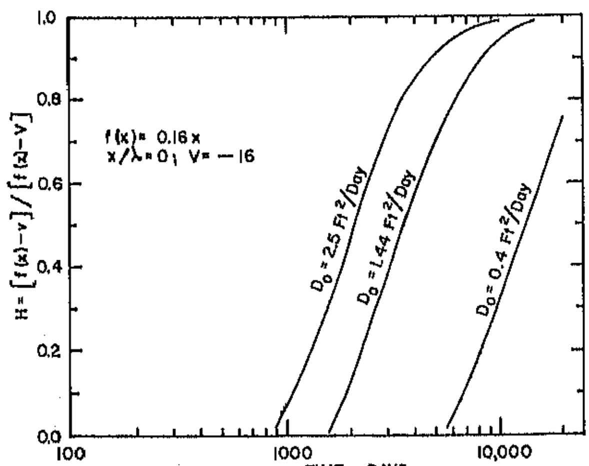


FIGURE 46.—Curves showing water-table responses (H) with time for three values of hydraulic diffusivity (D_o) when the initial condition was $f(x) = 0.16x$ and $V = -16$.

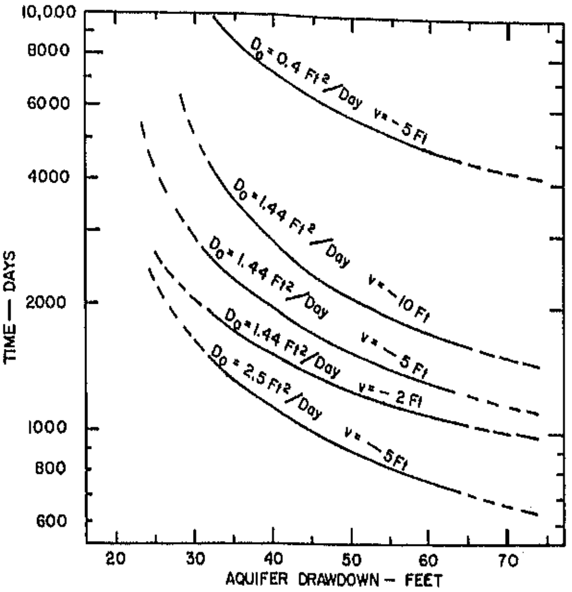


FIGURE 47.—Relationships between hydraulic diffusivity, (D_o), aquifer drawdown, and pumping time required to produce various amounts of water-table drawdown (v).

for the case where only 2 feet of water-table drawdown is desired, using the same hydraulic diffusivity (D_o = 1.44 ft^2/d), continuous pumping for 1,920 days (5.26 years) would be required at the same aquifer drawdown of 32 feet. An aquifer drawdown of 32 feet, in this hydraulic system, is equivalent to an imposed head of —16 feet (V = —16 feet).

Using the information, methods, and analyses described here enhances the possibility of designing a drainage well field and selecting pumping rates that will produce the required aquifer drawndowns. For example, if an aquifer drawdown of 32 feet is desired, several combinations of well spacings and pumping rates could be designed and used. The same criteria apply when either water-table drawdowns or lengths of pumping are the limiting factor.

The combined effects of hydraulic diffusivity and imposed hydraulic head on water-table response time were evaluated for three hydraulic diffusivities (fig. 47). Comparative time periods required to produce 2, 5, or 10 feet of water-table drawdown are shown as functions of imposed head (drawdown in the aquifer). Water-table response can be produced only by aquifer drawdowns greater than 16 feet because of the existing initial upward hydraulic gradient.

The well field, illustrated in figure 48, which is based on limited geologic and physical characteristics of both the aquifer and overburden, is used to describe principles of the analysis. The well field repre-

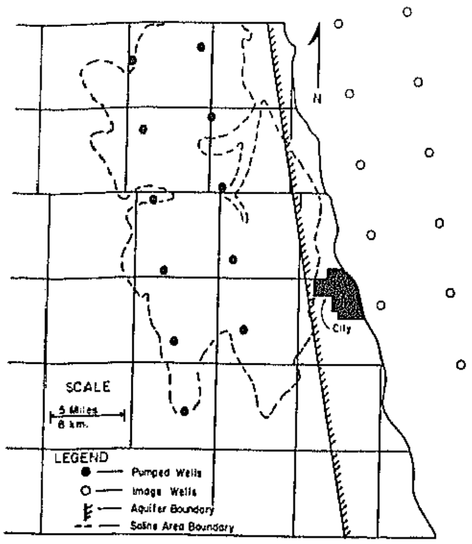


FIGURE 48.—Proposed drainage well field. Saline area is inside the dashed line.

sents one of many that could be used to drain this saline area in Grand Forks County. Existence of the geologic barrier on the eastern edge of the saline area increases the effectiveness of each pumped well (solid dots) by an amount equal to the effect produced by the image wells (open circles). These imaginary wells are used to duplicate, hydraulically, the effects on the flow system caused by a known physical boundary (23).

If the proposed drainage system of 11 wells were pumped at a rate of 500 gal/min, the aquifer drawdowns produced at the end of the given pumping periods would be as shown in table 10. Drawdowns at the wells are given in column 3; those in column 4 represent averages of the aquifer drawdowns for the 21 locations described by the midpoints of the diagonals between the wells and the outside corners of the grid squares. A drawdown of 32 feet at the diagonal midpoint would be achieved in less than a year and drawdown at the pumped well would be more than 66 feet. Pumping rate should be reduced upon achieving the 32 feet drawdown at diagonal midpoint to avoid excessive drawdowns that would dewater the aquifer. Dewatering of the aquifer would begin with a drawdown of 116 feet in the pumped

Table 10.--Aquifer drawdowns at the wells and wells' midpoints when pumping at a rate of 500 gpm for three periods

Pumping rate	Pumping period	Aquifer drawdown--feet	
		Pumped well	Diagonal midpoints
Gal/min	*Days*	*Feet*	*Feet*
500	180	66.9	30.6
500	365	83.8	45.3
500	1800	125.8	83.3

well; if the pumping rate remained constant, 116 feet of drawdown would occur after about 1,800 days of pumping.

The 11-well drainage system would be much less effective without presence of the barrier (fig. 48). Without the barrier, aquifer drawdown produced at the midpoint between four wells would be only 22.1 feet after pumping for 180 days at 500 gal/min. The presence of the aquifer boundary accounts for about 28 percent of the effective drawdown in the saline area.

Three methods for disposal of the saline pumped water can be suggested. The first would be to empty it directly into the Red River. Salt content of the pumped water was about 4,400 p/m. The well system, if each well is pumped at 500 gal/min, would yield about 12.25 ft^3/s. Average (for 89 years) flow of the Red River at Grand Forks, N. D., is 2,435 ft^3/s, but extremes have ranged from 80,000 ft^3/s to 2.4 ft^3/s (52). Using an average low flow of 280 ft^3/s for a 9-month period and a 10-year recurrence interval, the pumped drainage water would increase average salt concentration in the Red River by about 170 p/m. A second method would be to store the pumped saline water in a reservoir during periods of low flow and discharge it during periods of high river flow. A third disposal method could be to reclaim the water, process it for dry salt production, or both.

As previously stated, primary objective of the pump drainage system would be to stop the upward flow of artesian water and salts into the plant root zone and to lower the water table. The pump drainage system would not dewater the artesian aquifer nor would it remove all of the salt from the overburden. Stopping upward flow and lowering the water table would provide a depth of soil that would be leached free of salts by applying cultural practices and by making use of precipitation received in the area. Thus, in time and with good soil husbandry practices, a relatively salt-free root zone would be developed.

The proposed 11-well drainage system would reclaim the entire saline, poorly drained area in Grand Forks County. Each well then would benefit about 16,000 acres, and assuming that the well will cost about \$12,000 and have a life of 20 years, the pump and motor will cost \$63,000 and have a life of 5 years, the interest rate will be 7 percent, and the electric power will cost \$0.02/kwh, then the total annual pumping cost would be \$0.34 per acre. This cost includes neither the cost of a conveyance system nor a treatment or disposal system for the discharge waters.

Aside from the need for continuous pumping, pump drainage for the saline areas of Grand Forks County, and probably for all of the affected areas in the Red River Valley, would be technically and economically feasible.

Studies are under way to obtain more data on the physical properties of the overburden and aquifer system. This information will not only be useful and important in finalizing plans for the pump drainage system but would also reveal some of the possible adverse effects of pumping. For example, land subsidence could occur as a result of pumping for drainage. The effects of pumping on domestic water supplies would also require consideration.

Shallow well pump test (from the overburden)

The shallow production well was constructed in 1966 (fig. 49). Total depth of the well was 60 feet, extending through the lacustrine materials and terminating in the glacial drift. Three-foot sections of 4-inch well pipe alternating with 3-foot sections of 4-inch well screen were installed in the 20-inch drill hole; a 7-foot length of pipe was coupled to the alternating sections at 6 feet below the ground surface. Gravel pack in the well was of pea-sized rock. Pumping from the well was performed with an electric motor-driven submersible unit equipped with electrodes to maintain the water level within the well near the bottom.

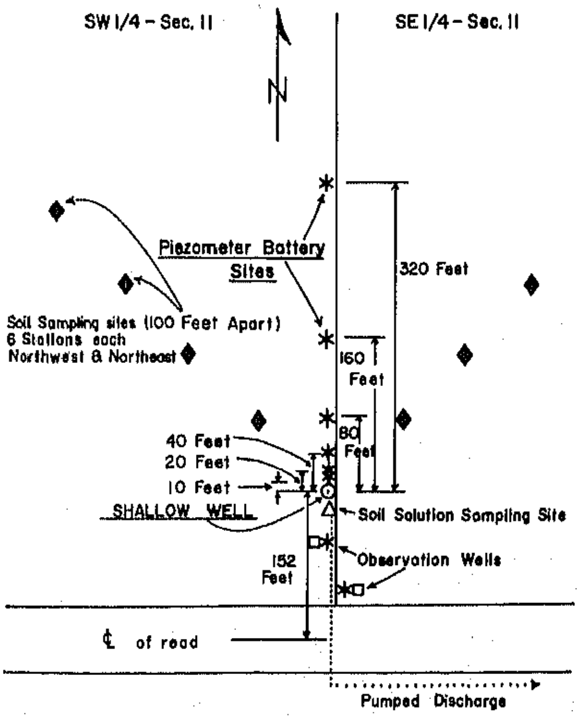


FIGURE 49.—Layout detail of the shallow well pump test experiment area.

Water pumped from the well was metered and discharged into a surface drain. The pump ran intermittently on demand.

A short-term pump test was performed on October 13 to 24 in 1967. Pumping was intermittent with an average rate of 15 gal/h. The average electrical conductivity of the water was 20.1 mmhos/cm.

A second pump test was conducted in 1968, from June 19 to October 24. The electrodes were set for the pump to start at 49 feet and stop when the water level in the well had been pumped down to 57 feet. Average pumping rate was 8.3 gal/h and the average EC of the water was 20.6 mmhos/cm.

The two pumping tests in 1967 and 1968 indicated that a longer pumping test was required to obtain water-table response in the overburden. Thus, the third pumping test, initiated on May 28, 1969, was continued except for stoppages caused by power outages and pump breakdowns until October 31, 1970 (521 days). Pump start-and-stop electrodes in the well maintained the water level between depths of 42 to 47 feet. Maximum water depth in the well had decreased as a result of fine materials settling in the well during the previous two nonpumping winter periods. During the third pumping test period, average discharge from the well was 13 gal/h and the average EC of the water was 21.3 mmhos/cm.

At the site, several piezometer batteries and observation wells were installed to evaluate water tables and profile piezometric heads (fig. 49). The piezometers north of the well, except for the battery 10 feet north, did not function properly as a result of gas in the systems (as described in the deep well test). Although they responded slowly because of the low conductance of the ceramic tips, these piezometers were later used as open systems and appeared to perform satisfactorily. The other piezometer batteries were all of the open-at-both-ends type and gave reliable readings.

Initial piezometric pressures show the typical upward gradient that indicates flow to the ground surface from underlying formations. Piezometric surface drawdowns at two dates—one year apart—measured by piezometers north of the pumped well, show that the greatest drawdown occurred near the well at a depth of 40 feet (fig. 50). The piezometric surface at this depth dropped 5 feet as the water table in the area rose about 2 feet during the first year of pumping. After the year of pumping, little response in pressure was indicated at 60 feet, a fair response at 20 feet, but a pronounced pressure decrease at 40 feet. The water-table rise resulted more from precipitation and surface conditions than from artesian pressures.

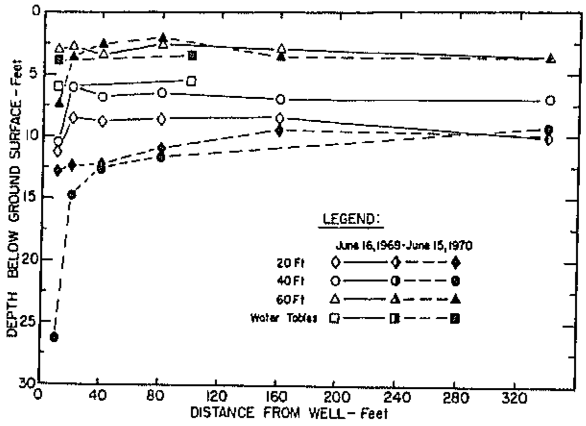


FIGURE 50.—Hydrographs of piezometers near the shallow well pump test at initiation and 1 year later.

Thus, the 1 year of continuous pumping did have a beneficial effect by creating drawdowns in the 40- and 20-foot piezometric pressures, but it did not have much influence on the 60-foot piezometric water level except near the well. The latter was to be expected because the pumping water level in the well was 42 to 47 feet. The radial distance influenced by pumping exceeded 320 feet, as shown by piezometric pressures in the 40-foot piezometers, and reached 320 feet as indicated by the 20-foot piezometers.

The lack of pumping influence on the water table is difficult to explain, but it probably is related to the rate that water could flow through the fine-textured overburden to the well. Additional sustained pumping should eventually lower the water table, but the system was not effective over the 3-year study.

DISCUSSION AND SUMMARY

General

Solutions to the problem could be either temporary or permanent reductions of soil salinity in the root zone.

Living with the Problem

- Impounding precipitation was effective in partially desalinizing a saline silt loam soil on a ridge in the ridge-depression micro-relief area. Single applications of leaching water were effective in initially reducing soil salt concentrations. After 3 years of cropping, however, applied leaching treatments had about the same profile salinity as the treatment receiving only natural precipitation.

Soil salinity remained high or increased with time in the treatment allowing precipitation to run off the plot. Wheat yields were significantly affected by soil salinity in the 6- to 16-inch soil depth. The regression of wheat yields on soil salinity was

$$Y = 68 - 8\ (EC) + 0.24\ (EC)^2$$

where Y is the yield in bushels per acre and EC is electrical conductivity of the saturation extract in mmhos/cm. Leaching had no ill effects on the soil complex.

- The practice of summer-fallowing for water conservation was also effective in reducing soil salinity. Under continuous cultivated fallow, barley and bromegrass, during a 3-year study, average soil salinity in the 0- to 24-inch depth was highest in the grass and lowest in the cultivated fallow. The water table was usually higher under the fallow. Wheat yields were increased fourfold on the fallow as compared to the barley treatment in the fourth cropping season. Salts leached were primarily chlorides but sulfates were also leached. The sodium-adsorption-ratio (SAR) decreased under fallow but increased under grass.

- One 3-year study to reduce soil salinity under continuous bare and applied straw mulch indicated salinity reductions under both treatments, but reductions were continuous under the straw compared to the bare treatment, in which changes were erratic. The fallow treatment needed periodic cultivating to maintain a soil mulch for sustained salinity reductions. The significant salinity reductions under straw mulch indicate that wheat yields could be increased by 10 to 20 bushels per acre.

  Soil salinity can be reduced and controlled under dryland conditions through the use of cultural practices which promote soil and water conservation. The combination of an overwinter straw mulch plus summer fallow was an effective treatment for maximizing the reduction of root zone soil salinity. Standing stubble was not as effective in reducing soil salinity overwinter as was an applied straw mulch.

- An overwinter cover of applied straw followed by cultivated summer fallowing effectively reduced soil salinity. Summer fallow and either a bare or straw cover overwinter almost tripled the yield of wheat compared with a bare overwinter and summer-cropped check treatment. The order of treatments by wheat yields were similar to the order of soil salinity reductions. Those treatments giving highest wheat yields and having the lowest soil salinity at the end of the 4-year experiment, in decreasing order for wheat

yields and increasing order for soil salinity, were straw-fallow; bare-fallow; flax-fallow; barley-fallow; straw-crop; flax-crop; barley-crop, and bare-crop. The most preferred treatment combination for soil salinity reductions and increased crop yields, over a long time, would be the winter straw cover with summer cropping and then periodically include summer fallow.

• Sugarbeet yields increased and soil salinity decreased by using black plastic film covering 85 percent of minor soil ridges between rows compared with the conventional flat planting system. A clear plastic germination cap over the row hastened emergence by 1 to 4 days.

Drainage for Water-Table and Salinity Control

• Shallow subsurface drainage was ineffective. The drains functioned only when the water table rose high enough to cover the drains and these rises occurred only intermittently.

Underground pipe drainage removed salts from the adjacent soil. Drains were at a depth of 5.5 feet and flow through the drains occurred only intermittently. Calculated outflow of salts through the drains was about 0.06 ton per acre annually. The total annual contribution of salts from artesian inflow (based on 0.5 inch of water) was about 0.25 ton per acre. Thus, the salt contribution from artesian inflow was four times greater than salt removal because of the tile drainage. Deeper placement of the tile drains, however, might have increased water and salt removal.

• Continuous pumping from the confined formation to reduce upward flow of artesian water and salts and to lower the water table is apparently the only permanent solution to the drainage and salinity problem. A long-term pump test from a single well indicated that a pump drainage system is economically feasible. This system would not dewater the artestian aquifer nor would it remove all of the salt from the overburden. A pump drainage system would reduce upward flow, lower the water table, and provide a depth of soil (plant root zone) below the ground surface that eventually would be leached free of salts by precipitation.

Well and Pump-Test Data Summary:

—The overburden consisted of 75 feet of lacustrine silts and clays and 36 feet of glacial till.

—Top of the 63-foot thick sandstone aquifer was at 111 feet.

—Artesian pressure in the aquifer (static) was 6 feet above ground surface.

—Transmissibility (T) of the sandstone aquifer was 45,000 gallons per day per foot.

—Storage coefficient (S) of the sandstone aquifer was 2.2×10^{-4}.

—Horizontal hydraulic gradient of the sandstone aquifer was 5 ft/mi to the east.

—Vertical hydraulic gradient in the overburden was 0.16.

—Vertical hydraulic conductivity of the overburden was 0.01 in/d.

—Vertical flow contribution from the aquifer into the overburden was evaluated as 0.5 in/yr.

Overburden Drainage Analysis:

—The 179-pump test data, combined with an analysis that assumed pressure redistribution in the overburden was analogous to linear flow of heat in a slab, was used to evaluate hydraulic diffusivity of the overburden.

—Calculated hydraulic diffusivities averaged 1.44 ft^2/d indicating that hydraulic head in the overburden will readjust very slowly after a head reduction at the aquifer-overburden interface.

—The natural water table fluctuated between ground surface and 14 feet. In the overburden drainage analysis, an average depth of 10 feet was used.

—The length of time required to effect hydraulic head redistribution (and subsequent water-table and salinity control) depended on the hydraulic diffusivity of the overburden.

A Proposed Pump Drainage System (based on data from the one pump test):

—The total drainage system would consist of 11 wells pumping from the artesian formation.

—Each well would be pumped at $\leq$ 500 gal/min.

—Each well would reclaim or benefit about 16,000 acres of saline land.

—Continuous year-round pumping would be required and would lower the water table 2 feet in 5.3 years or 5 feet in 7.1 years with an aquifer drawdown of 32 feet.

—Cost of the drainage system and operating costs (based on 7 percent interest) would be about $0.34 per acre annually.

—If all of the drainage discharge water were emptied into the Red River of the North, the probable increase in salt concentration at average river flow would be about 22 p/m. At average low flow of the Red River, the salt concentration would increase by 170 p/m because of pump drainage.

—Studies are underway to evaluate formation thicknesses, overburden characteristics, and possible adverse effects of pumping on land subsidence and domestic water supplies.

• Continuous pumping from the overburden formation (from a shallow well, unconfined aquifer test) indicated that the piezometric head can be reduced in some layers, but lowering the water table by this method would be a slow process. More than a year of continuous pumping and two separate summer pump tests produced only limited water-table effects.

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APPENDIX

Table 11.--Climatic data for Grand Forks, North Dakota area[1/]

Month	Air temperatures[1/] Extremes Max.	Min.	Mean daily max.	Mean daily min.	Ave.	Precipitation[1/] Ave.	Snow-fall	Ave. snow depth[2/]	Evaporation USWB[3/] pan
	°F	*°F*	*°F*	*°F*	*°F*	- - - *Inches*	- - -	-	*Inches*
January	37	-29	14.4	-5.8	4.3	0.56	6.2	6.0	
February	40	-26	18.4	-1.7	8.4	.55	5.9	6.7	
March	53	-12	32.7	13.4	23.1	.77	5.5	4.5	
April	75	14	52.5	30.7	41.6	1.65	3.0	.4	
May	87	26	66.8	41.8	54.3	2.50	.4	0	
June	91	37	75.3	51.6	63.5	3.48	0	0	3.15
July	94	44	81.4	56.6	69.0	2.85	0	0	6.91
August	94	40	79.6	54.1	66.9	2.80	0	0	8.02
September	89	27	68.9	44.5	56.7	1.86	T	0	8.22
October	78	16	55.7	33.2	44.5	1.30	1.2	.02	2.85
November	57	-5	35.5	17.8	26.7	.90	6.1	1.4	
December	41	-22	20.4	1.9	11.2	.60	6.2	4.3	
Total						19.82	34.5		
Mean annual			50.1	28.2	39.2	19.82			

1/ Temperature and precipitation data taken by FAA at Grand Forks Municipal Airport. Long-term means compiled by Weather Bureau, State Climatologist, in cooperation with University of North Dakota Weather Bureau Station (82 years of records, 1891-1972).

2/ Average of 9 years (1957-66) record, FAA, Grand Forks.

3/ Average of 5 years (1959-63) record, USDA-ARS-SWC. May 15 through September 15. Class A, U.S. Weather Bureau pan.

Table 12--Chemical composition of six soil profiles in the saline area

Depth	Texture[1/]	pH	Saturation	Saturation extract: Elect. Cond.	Ca	Mg	Na	Na	SO4	Cl	B	Exch. Na	CEC	Organic carbon
Inches			*Percent*	*Mmhos/cm*	- - - *Meq/l*	-	-	*Percent*	*Meq/l*	*Meq/l*	*P/m*	*Percent*	*Meq/100g*	*Percent*
NW¼ sec. 9, T. 152 N., R. 51 W. (Rye Twp.) Profile 5, Glyndon silty clay loam, on lacustrine sediments														
0-8	SiCL[2/]	7.2	73	27	73	71	171	54	66	243	0.3	11	42	5.0
8-16	SiCL[2/]	7.4	59	28	63	104	148	47	29	284	.1	12	24	1.8
16-22	SiL[2/]	7.4	48	28	59	128	130	41	22	293	.1	12	14	.7
22-43	Si[2/]	7.2	42	40	20	215	72	37	31	448	.1	17	12	.4
43-72	SiL[2/]	7.1	48	55	136	314	238	35	38	648	.2	18	15	.5
NE¼NW¼ sec. 8, T. 151 N., R. 51 W. (Brenna Twp.) Profile 8, Bearden silty clay loam on lacustrine sediments (on ridge)														
0-5	SiCL[2/]	7.6	74	10	27	61	53	37	105	29	0.3	7	40	4.4
5-12	SiCL	7.7	65	12	27	78	66	39	114	53	.1	8	30	2.7
12-19	SiL[2/]	7.8	44	9	10	45	51	48	55	48	.1	10	14	.9
19-34	SiCL[2/]	7.4	69	16	28	106	85	39	140	75	.1	14	27	.4
34-72	SiCL[2/]	7.4	75	18	29	148	90	34	160	107	.1	15	27	.3
NE¼NW¼ sec. 8, T. 151 N., R. 51 W. (Brenna Twp.) Profile 16, Bearden silt loam on lacustrine sediments (in depression)														
0-13	SiCL	7.6	63	2	[3/]15		1	8						
13-29	SiCL	7.7	54	1	4		4	47						4.0
29-49	SiCL	7.7	50	1	8		4	32						1.0
49-63	SiCL	7.6	66	2	19		3	14						
63-84	SiCL	7.5	74	3	30		3	9						
NW¼ sec. 8, T. 150 N., R. 51 W. (Allendale Twp.) Profile 10, Grimstad fine sandy loam, on glacial till														
0-5	fSL[2/]	7.8	45	8	38	46	18	17	68	30	0.5	3	26	3.1
5-11	fSL	7.5	36	6	31	44	13	15	67	18	.2	3	18	1.6
11-25	gSL[2/]	7.8	28	6	17	57	13	14	71	18	.5	4	7	.6
25-32	CL[2/]	7.8	49	7	25	67	11	10	84	18	.4	4	15	.3
32-72	CL[2/]	7.8	43	6	25	55	9	9	80	8	.3	3	10	[4/]nd
NW¼ sec. 36, T. 151 N., R. 52 W. (Oakville Twp.) Profile 12, Hamerly clay loam, on glacial till														
0-5	CL[2/]	7.8	77	5	20	11	33	51	39	18	0.8	7	43	5.8
5-11	CL[2/]	7.5	61	9	29	21	68	58	89	26	1.1	14	22	1.8
11-18	CL	7.8	61	11	25	19	87	66	103	26	.5	22	17	.4
18-30	CL[2/]	7.8	60	12	25	19	107	70	108	42	.3	29	15	.2
30-54	CL	7.8	60	12	22	16	109	74	96	49	.4	34	12	nd
NE¼NE¼ sec. 9, T. 151 N., R. 52 W. (Oakville Twp.) Profile 13, Sletten silty clay loam, poorly drained lacustrine (till at 63 inches)														
0-10	SiCL	7.4	75	20	50	35	128	60	32	175	0.5	15	42	4.1
10-18	SiCL	7.4	75	21	51	44	147	50	61	178	.4	20	36	2.1
18-31	SiL	7.4	57	28	55	66	191	61	29	281	.2	27	21	.4
31-63[5/]	SiL	7.4	62	34	78	88	221	55	38	348	.3	24	20	.2
65-96	CL	7.4	42	22	50	43	139	60	26	206	.7	23	11	nd
96-144	CL	7.3	43	14	29	24	97	65	34	114	1.3	21	10	nd
NE¼ sec. 21, T. 154 N., R. 52 W. (Levant Twp.) Profile 15, Bearden silty clay loam, on lacustrine sediments														
0-6	SiCL[2/]	7.4	79	11	51	31	47	36	41	84	0.2	5	51	6.0
6-13	SiCL[2/]	7.4	70	10	44	31	45	38	52	65	.1	7	28	1.9
13-30	SiL	7.3	57	17	58	56	66	37	28	150	.1	10	20	.5
30-54	SiCL	7.1	73	25	100	109	82	28	38	252	.1	9	25	.6
54-78	SiC[2/]	7.2	82	24	96	91	82	31	37	231	.1	10	27	nd
78-144	SiC	7.4	79	26	104	89	102	35	34	258	.1	12	27	nd

1/ C = clay, L = loam or loamy, Si = silt or silty, S = sand or sandy, g = gravel or gravelly, f = fine.
2/ Determined by laboratory analysis; others estimated by feel.
3/ Ca plus Mg.
4/ Not determined.
5/ Gravelly sand layer 63-65 inches overlying firm glacial till on Profile 13 was not sampled.

Table 13.--Composition of soil saturation extracts from 12-foot profiles in an area northwest of the hydrologic study area, Grand Forks County, N. Dak.

Location	Depth	Texture[1]	Electrical conductivity	Soluble cations Na	Soluble cations K	Soluble cations Ca+Mg	Soluble Na	SAR
	Inches		*Mmhos/cm*	--*Meq per liter*---			*Percent*	
NW¼ 9, T. 152 N., R. 53 W., (Interbeach), lacustrine sediments	0-30	SL	0.4	0.3		4	8	2
	30-60	S	.3	.3		3	10	3
	60-78	S	.3	.2		2	11	3
	78-90	S	.3	.5		2	15	5
	90-102	S	.5	1.1		4	22	1
	102-132	CL[2]	1.0	1.9		8	19	1
	132-150	CL-C[2]	1.7	2.7		14	16	1
NW¼ 3, T. 152 N., R. 53 W., lacustrine sediments	0-12	SiCL	3.1	10		21	32	3
	12-24	SiCL	5.0	21		34	38	5
	24-34	SiCL	9.2	48		62	44	9
	36-60	SiCL	12.4	68		82	45	11
	60-78	SiCL	10.4	65		68	47	10
	78-114	SiCL	8.2	45		53	46	9
	114-120	SL	8.0	38		55	40	7
	120-150	CL	7.6	39		51	43	8
NW¼ 36, T. 152 N., R. 53 W., lacustrine sediments	0-6	SiCL	4.5	15		35	30	4
	6-24	SiCL	7.8	38		56	40	7
	24-36	SiCL	9.5	43		72	37	7
	36-72	SiCL	16.0	61		143	30	8
	72-90	SiL	17.6	68		162	30	8
	90-102	gCL	13.2	46		115	28	6
	102-126	CL[2]	12.0	43		107	29	6
	126-150	CL[2]	10.3	37		88	30	6
SE¼ 18, T. 153 N., R. 52 W., lacustrine sediments	0-6	SiL	17.6	120	0.3	110	52	16
	6-12	SiL	20.8	152	.2	218	56	15
	12-30	SiL	19.6	136	.2	119	53	18
	30-60	SiL-SiCL	27.2	180	.2	185	49	19
	60-84	SiCL	22.8	148	.2	152	49	17
	84-132	C	16.8	132	.3	83	61	20
	132-150	C	14.8	124	.5	60	44	23
NE¼ 3, T. 153 N., R. 52 W., lacustrine sediments	0-6	SiL	9.0	54	.7	55	49	10
	6-18	SiL	10.0	52	.3	70	43	9
	18-30	SiL	11.6	74	.2	71	51	12
	30-54	SiCL	14.4	75	.3	110	41	10
	54-90	SiCL	11.0	50	.3	85	37	8
	90-138	C	10.0	40	.3	83	33	6
	138-150	C	16.0	68	.5	136	33	8
SW¼ 17, T. 154 N., R. 51 W., lacustrine sediments	0-6	SiL	5.4	13	.2	49	21	3
	6-12	SiL	8.8	27	.2	78	26	4
	12-30	SiL	15.0	55	.3	135	29	7
	30-54	SiL	19.6	70	.5	184	27	7
	54-90	SiCL	16.0	53	.5	151	26	6
	90-132	C	16.0	53	.5	151	26	6
	132-150	C	13.6	44	.5	125	26	6

[1] Texture by feel. Sodium adsorption ratio (SAR) = $Na/\sqrt{(Ca+Mg)/2}$.

[2] Compact glacial till, usually overlain with a thin coarse-textured washed contact zone between it and lacustrine sediments.

Table 14.--Particle size analyses of selected horizons from principal soils of the area

Horizon	Depth	v.c.[1] sand 2.-1	c. sand 1-0.5	m. sand 0.5-0.25	f. sand 0.25-0.1	v.f. sand 0.1-0.05	Total sand 2-0.05	Silt .05-.002	Clay <.002	>2mm	Texture
	Inches	Percent									
Profile 5, NW¼ sec. 9, T. 152 N., R. 51 W. (Rye Twp.) - lacustrine											
A	0-8	0.1	0.5	0.3	1.5	1.9	4.3	62.4	33.3	0	SiCL
A	8-16	.0	.2	.2	.5	1.8	2.6	67.9	29.5	0	SiCL
C	32-43	.0	.1	.2	.6	1.7	2.6	87.1	10.3	0	Si
C	54-72	.3	.3	.2	.4	.6	1.8	83.5	14.7	0	SiL
Profile 15, NE¼ sec. 21, T. 154 N., R. 52 W. (Levant Twp.) - lacustrine											
A	0-6	0.2	0.2	0.2	0.8	2.0	3.4	60.6	36.0	0	SiCL
A	6-13	.2	.4	.2	.7	2.7	4.2	57.7	38.1	0	SiCL
C	13-30	.1	.2	.3	.9	1.7	3.2	71.9	24.9	0	SiL
C	54-78	.2	.4	.3	.8	.5	2.2	54.3	43.5	0	SiC
Profile 8, Ridge, NE¼NW¼ sec. 8, T. 151 N., R. 51 W. (Brenna Twp.) - lacustrine											
A	0-5	0.1	0.5	0.3	1.0	2.1	4.0	65.3	30.7	0	SiCL
C	12-19	.0	.1	.2	.8	5.9	7.0	75.4	17.6	0	SiL
C	19-27	Too gypsiferous to analyze, class estimated								0	SiCL
C	56-72	.2	.4	.3	.5	.6	2.0	62.4	35.6	0	SiCL
Profile 16, Depression, NE¼NW¼ sec. 8, T. 151 N., R. 51 W. (Brenna Twp.) - lacustrine											
A	0-7	0.0	0.5	0.4	1.0	2.2	4.1	67.1	28.8	0	SiCL
A	13-16	0.1	0.4	0.4	2.0	4.5	7.4	60.7	31.9	0	SiCL
C	16-29	0.2	0.5	0.4	1.0	2.2	4.3	65.1	30.6	0	SiCL
C	29-40	0.3	0.9	0.7	1.0	1.2	4.1	67.3	28.6	0	SiCL
C	49-55	1.1	0.8	0.5	1.0	1.2	4.6	62.8	32.6	0	SiCL
C	66-84	0.6	0.4	0.3	0.4	0.3	2.0	59.2	38.8	0	SiCL
Profile 10, NW¼ sec. 8, T. 150 N., R. 51 W. (Allendale Twp.) - glacial											
A	0-5	3.8	9.9	13.0	21.3	6.5	54.4	29.3	16.3	0	fSL
D	11-18	11.7	8.9	13.1	23.3	5.1	62.0	27.2	10.8	20	gSL
D	25-32	3.2	4.3	4.6	9.6	4.7	26.4	43.7	29.9	5	CL
D	54-72	3.8	3.9	3.5	9.0	6.8	27.0	53.0	20.0	9	SiL
Profile 12, NW¼ sec. 36, T. 151 N., R. 52 W. (Oakville Twp.) - glacial											
A	0-5	2.0	4.4	4.2	8.9	7.0	26.5	41.7	31.8	0	CL
A	5-11	3.2	5.3	4.4	8.3	7.7	28.9	36.2	34.9	0	CL
D	18-30	3.2	3.2	2.6	6.8	5.2	21.0	49.0	30.0	6	CL
D	30-54	3.9	4.1	3.2	7.7	5.5	24.4	52.9	22.7	6	CL

[1] v = very, c = coarse, m = medium, f = fine.

Table 15.--Soil water retention, bulk densities, and hydraulic conductivities of some soils

Depth	Horizon	Texture	Water retained at atmospheres tension 0.3 Atm.	0.8 Atm.	15 Atm.	Bulk density	Hydraulic conductivity Cores	Mixed soils	Auger hole	Piezometer method
Inches			*Percent by volume*			*g/cm³*	*- - - - -Inches per hour- - - - -*			
Profile 5, NW¼ sec. 9, T. 152 N., R. 51 W. (Rye Twp.) - lacustrine										
0-8	A	SiL-L	42	33	20			2.20		
8-16	A	SiL-L	30	23	14			2.30		
32-43	C	SiL-SiCL	22	13	6			.50	2.10	
54-72	C	SiL-SiCL	32	20	9			.30		0.20
Profile 8, (ridge site), NE¼NW¼ sec. 8, T. 151 N., R. 51 W. (Brenna Twp.) - lacustrine										
0-5	A	SiL	41	31	20					
12-19	C	SiL	20	14	8			1.80		
19-27	C	SiCL	37	28	19					
24-36	C	SiCL						.20		
36-72	C	SiCL-SiC						.04		
56-72	C		46	40	22					
102-112	C	SiCL-SiC							0.08	
112-120	C	SiC							.01	
Profile 9, NW¼ sec. 33, T. 151 N., R. 51 W. (Brenna Twp.) - lacustrine-glacial										
0-8	A	SiCL	41	33	19					
8-20	A	SiCL	30	24	15		0.03	1.80		
20-31	C	SiCL	32	26	18	1.29				
30-42	C	SiCL				1.31	.20*			
42-66	C	SiCL	39	33	19	1.32		.20		
48						1.28	.09*			
72-89	D	CL(till)	28	23	18			.08		
Profile 10, NW¼ sec. 8, T. 150 N., R. 51 W. (Allendale Twp.) - glacial										
0-5	A	L	25	19	12					
0-12							5.20	1.90		
11-18	C	gL	14	10	6	1.61				
12-24							.20	3.00		
25-32	C	CL	27	21	6	1.33		.50		
54-72	C	CL	22	19	6	1.76	.40*	.25	1.60	
Profile 12, NW¼ sec. 36, T. 151 N., R. 52 W. (Oakville Twp.) - glacial										
0-5	A	SiL	41	36	25	1.06	1.90	1.00		
5-11	A	SiL	35	29	18			.16		
18-30	D	CL till	26	22	14	1.49	.02			
36						1.63	.01*			
30-54	D	CL till	24	21	11			.06	.12	
Profile 13, NE¼ sec. 9, T. 151 N., R. 52 W. (Oakville Twp.) - lacustrine-glacial										
0-10	A		44	40	26	1.01				
10-18	A		44	37	22	1.21				
18-31	C		37	28	15	1.22	1.40			
31-39	C		39	28	16	1.22	.80	0.01		
39-63	C		41	31	16	1.21		.10		
Profile 14, SW¼ sec. 28, T. 151 N., R. 52 W. (Oakville Twp.) - washed glacial										
0-8	A	fSL	15	12	7					
8-20	C	fSL	13	11	6			1.80		
32-40	C	fSL	24	18	9	1.45	0.30			
40-48	C	LfS	10	8	4	1.46	2.00	.10		
48-55	C	LfS	10	10	5		0.08			
55-72	C	CL till	30	27	14	1.60		.04		
Profile 15, NE¼ sec. 21, T. 154 N., R. 52 W. (Levant Twp.) - lacustrine										
0-6	A	SiL	46	28	24					
6-13	A	SiCL	40	31	19			0.35		
13-30	C	SiCL	32	25	12			.04		
54-78	C	C	41	36	22			.04		
Profile 16, (depression site), NE¼NW¼ sec. 8, T. 151 N., R. 51 W. (Brenna Twp.) - lacustrine										
0-7	A	SiL	35	28	18					
13-16	A	SiCL	32	26	17					
16-29	C	SiL	27	22	13					
29-40	C	SiL	28	21	11					
66-84	C	C	45	38	20	1.23				0.70

* Horizontal soil core

Table 16.--Specific yields and bulk densities of several lacustrine soils in the saline area[1]

Depth	Estimated texture	Bulk density[2]	Specific yield[2]	Depth	Estimated texture	Bulk density[2]	Specific yield[2]
Inches		*g/cm³*	*Percent*	*Inches*		*g/cm³*	*Percent*
Profile 16, site 1, N½ sec. 8, T. 151 N., R. 51 W. (Brenna Twp.) (nonsaline depression)							
54-57	SiCL	1.25	6.5	78-81	SiCL	1.24	2.4
57-60	SiCL	1.25	5.1	81-84	SiCL	1.20	2.6
60-63	SiCL	1.26	4.7	84-87	SiCL	1.21	2.6
63-66	SiCL	1.26	3.9	87-90	SiCL	1.23	2.7
66-69	SiCL	1.27	2.9	90-93	SiCL	1.25	2.2
69-72	SiCL	1.26	3.4	93-96	SiC	1.20	1.6
72-75	SiCL	1.24	3.3	96-99	SiC	1.20	1.4
75-78	SiCL	1.25	2.4	99-102	SiC	1.24	1.8
Site 2,[3] S½ sec. 11, T. 152 N., R. 51 W. (Rye Twp.) (Glyndon SiL or SiCL-saline)							
3-6	SiL	1.04	6.6	54-57	SiCL	1.25	3.1
6-9	SiL	1.00	14.0	57-60	SiCL	1.28	2.9
9-12	SiL	1.02	13.7	60-63	SiCL	1.13	2.8
12-15	SiL	1.17	10.9	63-66	SiCL	1.29	2.0
15-18	SiL	1.34	7.0	66-69	SiC	1.22	2.0
18-21	SiL	1.39	6.9	69-72	SiC	1.26	2.7
21-24	SiL	1.36	6.4	72-75	SiC	1.23	3.9
24-27	SiL	1.29	7.2	75-78	SiC	1.26	2.3
27-30	SiL	1.25	7.1	78-81	SiC	1.29	1.9
30-33	Si	1.27	6.9	81-84	SiC	1.22	1.8
33-36	Si	1.32	5.1	84-87	SiC	1.20	1.4
36-39	Si	1.32	4.7	87-90	SiC	1.26	2.6
39-42	Si	1.38	3.5	90-93	SiC	1.07	5.5
42-45	Si	1.29	5.4	93-96	SiC	1.14	2.0
45-48	SiCL	1.27	3.4	96-99	SiC	1.16	2.0
48-51	SiCL	1.28	4.2	99-102	SiC	1.23	1.4
51-54	SiCL	1.23	4.0	102-105	SiC	1.15	1.1
Profile 13, site 3, NE¼ sec. 9, T. 151 N., R. 52 W. (Oakville Twp.) (glacial till at 63 inches)							
3-6	SiCL	0.97	15.1	39-42	SiL	1.27	2.6
6-9	SiCL	1.06	11.7	42-45	SiL	1.23	1.8
9-12	SiCL	1.06	9.7	45-48	SiL	1.22	1.7
12-15	SiCL	1.23	5.0	48-51	SiL	-	1.5
15-18	SiCL	1.25	5.0	51-54	SiL	1.24	1.5
18-21	SiL	1.29	4.7	54-57	SiL	1.21	1.2
21-24	SiL	1.27	5.4	57-60	SiL	1.19	1.6
24-27	SiL	1.22	5.6	60-63	CoS	1.56	10.4
27-30	SiL	1.27	3.8	63-66	CoS	1.71	7.3
30-33	SiL	1.28	3.9	66-69	CL	1.84	1.2
33-36	SiL	1.27	3.1	69-72	CL	1.83	3.2
36-39	SiL	1.22	3.0	72-75	CL	1.81	1.6

1/ Soil cores (Uhland) saturated at least 48 hours and drained with 70 cm water tension for 36 hours.

2/ Average of three cores per depth increment.

3/ No profile number given; for detailed chemical properties see reference 8.

Table 17.--Domestic well depths, pressures [feet of water above (+) or below (-) ground surface], flows, and water salinity from 44 wells in or near the hydrologic study area

Location Sec., T., R.	Depth	Pressure	Flow	Elect. Cond. 1957	Elect. Cond. 1959
	Feet	*Feet*	*Gal/min*	*Mmhos/cm*	
SW. 36, 152 N., 52 W.	90	13.8	2		8.2
SE. 35, 152 N., 52 W.	198	5.8	3		6.8
SE. 35, 152 N., 52 W.	165			8.0	
NE. 12, 152 N., 52 W.	150				7.3
SW. 1, 152 N., 52 W.	40		3	8.5	9.3
NE. 11, 152 N., 52 W.		-4.0			6.1
NW. 13, 152 N., 52 W.	100	-12.0	>1	6.6	6.1
SW. 3, 152 N., 52 W.	40	-4.0			10.4
NE. 9, 152 N., 52 W.	>60	-6.0			6.8
NE. 7, 152 N., 52 W.	186		<1		14.4
S. 6, 152 N., 52 W.	64		3	6.6	5.7
NW. 19, 152 N., 52 W.	78			6.5	7.1
NW. 20, 152 N., 52 W.	87	> .0	<1	12.8	10.0
SE. 18, 152 N., 52 W.	70	> .0	>1		5.0
NW. 15, 152 N., 52 W.	52				8.5
NE. 15, 152 N., 52 W.	168			16.4	13.2
SW. 24, 152 N., 52 W.	260	-4.0		8.6	7.7
NE. 24, 152 N., 52 W.		4.8			5.9
NW. 28, 152 N., 52 W.					12.8
SE. 33, 152 N., 52 W.	150				11.5
SW. 31, 152 N., 52 W.	86			8.0	
NW. 30, 152 N., 52 W.	118			6.5	
SE. 14, 151 N., 52 W.	70				10.4
N. 30, 151 N., 52 W.	140	-18.0			10.2
SW. 2, 151 N., 52 W.	185	6.9	2		12.8
NW. 2, 151 N., 52 W.	180			16.0	
SE. 1, 151 N., 52 W.	250	16.1			6.0
NE. 12, 151 N., 52 W.	65	5.8			7.2
NE. 26, 151 N., 52 W.			15		6.4
SE. 23, 151 N., 52 W.	116	11.6	36		9.8
SE. 31, 152 N., 51 W.	149	11.6			6.7
SW. 25, 152 N., 51 W.		2.5		7.0	5.7
NW. 12, 152 N., 51 W.	100	1.5	1	7.5	6.8
SW. 12, 152 N., 51 W.	220	.8		10.0	8.5
NW. 9, 152 N., 51 W.		.7		7.8	8.0
SW. 4, 152 N., 51 W.		.2		8.4	7.2
NW. 6, 152 N., 51 W.	140	.0		6.8	
NW. 19, 152 N., 51 W.	147	4.6		6.5	
NE. 11, 152 N., 51 W.				10.0	
NE. 10, 152 N., 51 W.	160			8.3	
SW. 8, 152 N., 51 W.	100			8.0	
NE. 8, 152 N., 51 W.	85				8.0
SE. 19, 152 N., 51 W.	123			5.8	
SW. 34, 152 N., 51 W.	103	2.9	1	6.3	
W. 10, 152 N., 52 W.	300			15.6	
SW. 24, 152 N., 52 W.	19			14.0	
SE. 34, 151 N., 51 W.	195	26.5	10		6.1
SE. 27, 151 N., 51 W.	258	24.2			5.5
NE. 33, 151 N., 51 W.	126	5.2			6.3
SW. 28, 151 N., 51 W.	160	20.7	>10		5.4
SW. 33, 151 N., 51 W.		3.3			6.6
NW. 32, 151 N., 51 W.		19.6			6.6
SW. 5, 151 N., 51 W.	125	20.7		6.5	5.6
NE. 2, 151 N., 51 W.				6.5	
N. 6, 150 N., 52 W.	90				4.8
SW. 9, 152 N., 50 W.	150	.5	<1		7.6
NE. 28, 152 N., 50 W.	99	-3.0			6.6
SW. 35, 153 N., 51 W.				8.2	
SE. 35, 153 N., 51 W.				8.0	
N. 11, 151 N., 52 W.					11.0
NW. 1, 151 N., 52 W.					6.8
NW. 12, 151 N., 52 W.	69	3.5		11.2	8.5
NW. 32, 151 N., 52 W.	120	-15.0			3.4
NW. 33, 151 N., 52 W.	267	-15.0			10.5
NW. 28, 151 N., 52 W.	240	-20.0			11.0
NW. 27, 151 N., 52 W.	210	5.8			11.4
SW. 31, 152 N., 51 W.	165	9.8	3		6.4
SW. 31, 152 N., 51 W.	165	6.9	3		6.4
SW. 31, 152 N., 51 W.	195			7.8	
SE. 10, 152 N., 51 W.	100		<1	7.3	6.4
NE. 8, 152 N., 51 W.	85		>1		8.0
SW. 5, 152 N., 51 W.	100	2.8	3		7.3
SW. 5, 152 N., 51 W.	120	3.5	>1	8.3	7.4
SW. 32, 152 N., 51 W.	113			6.3	
NW. 34, 152 N., 51 W.	130			6.4	
SW. 21, 152 N., 51 W.	220			10.8	
SE. 4, 152 N., 51 W.				6.7	
SE. 30, 152 N., 51 W.	120			6.0	
USGS Wells (In 1967)					
SW. 32, 153 N., 52 W.	116	12.6			8.0
SE. 18, 153 N., 52 W.	126	10.7			7.4
		Av.		8.6	7.9

Table 18.--Artesian pressure losses in the soil profile as measured by piezometer batteries

Location Sec., T., R.	Date	Depth increment below ground surface	Increment head loss	Gradient of loss (upward)	Surface saline conditions
		Feet	*Feet*	*Feet/foot*	
SW. 30, 152 N., 50 W., (Ridge)	1958	58 to 27	7.43	0.24	Moderate
SW. 30, 152 N., 50 W., (Ridge)	1958	27 to 17	.22	.02	Moderate
SW. 30, 152 N., 50 W., (Depression)	1958	27 to 17	.67	.07	Slight
SW. 16, 152 N., 50 W.	1958	58 to 38	2.57	.13	Nonsaline
SW. 16, 152 N., 50 W.	1958	38 to 18	1.30	.06	Nonsaline
SW. 14, 152 N., 51 W.	1958	58 to 38	2.80	.14	High
SW. 14, 152 N., 51 W.	1958	38 to 18	4.72	.24	High
NW. 9, 152 N., 51 W.	1958	58 to 38	1.04	.05	High
NW. 9, 152 N., 51 W.	1958	38 to 18	5.85	.29	High
NW. 19, 152 N., 51 W.	1958	58 to 38	5.00	.25	Moderate
NW. 19, 152 N., 51 W.	1958	38 to 18	.95	.05	Moderate
N. 8, 151 N., 51 W.	1959	60 to 40	8.33	.42	Moderate
N. 8, 151 N., 51 W.	1959	40 to 30	1.08	.11	Moderate
N. 8, 151 N., 51 W.	1959	30 to 20	1.33	.13	Moderate
NW. 21, 152 N., 52 W.	1966	50 to 30	1.35	.07	Moderate
NW. 21, 152 N., 52 W.	1966	30 to 20	1.10	.11	Moderate
		60 to 20	3.01	.08	High
		37 to 20	2.98	.18	High
		50 to 30	1.04	.05	Low
		to 30	3.30	.16	Low
		to 30	2.80	.14	Low
		to 30	3.50	.18	Moderate
		to 30	1.70	.08	Nonsaline
		to 26.7	2.78	0.14	

Table 19.--The chemical composition of waters from some flowing and nonflowing artesian wells and one nonartesian well in or near saline areas

Location Sec., T., R.	Depth	Type	Elect. cond.	B	Cations Ca	Mg	Na	K	Na[1]	SAR	Anions HCO_3	SO_4	Cl
	Feet		*Mmhos/cm*	*P/m*	- - -	*Meq/l*	- - -	- - -	*Percent*		- - -	*Meq/l*	- - -
34, 152 N., 51 W.	103[2]	Flowing artesian	6.4	2.0	14	5	50	1.2	72	16	4	32	33
30, 152 N., 52 W.	118	Flowing artesian	6.7	3.2	12	8	53	1.4	71	16	4	32	37
23, 151 N., 52 W.	90	Flowing artesian	12.4	3.6	22	115	85	2.0	38	11	3	36	86
17, 153 N., 51 W.	175	Flowing artesian	17.3	3.8	28	19	143	1.9	75	29	5	37	148
31, 152 N., 51 W.	105	Flowing artesian	6.5	3.0	12	7	49	1.2	70	16	4	32	34
33, 153 N., 51 W.	120	Flowing artesian	7.6	2.9	13	7	60	1.1	73	19	4	30	47
27, 153 N., 51 W.	?	Flowing artesian	8.4	2.8	18	8	65	0.9	71	18	4	29	58
33, 152 N., 51 W.	240	Flowing artesian	10.8	3.0	19	13	83	1.6	71	21	4	30	80
9, 152 N., 51 W.	?	Artesian	8.0	3.0	13	7	64		75			30	51
18, 152 N., 51 W.	160	Artesian	6.9	3.2	13	8	53	1.3	71	17	4	33	38
25, 152 N., 51 W.	110	Flowing artesian	6.8	2.8	13	6	53	1.1	73	17	4	32	37
32, 152 N., 51 W.	?	Flowing artesian	72.5	12.1	81	52	724	9.0	83	89	3	63	819
7, 150 N., 54 W.[2]	40	Nonartesian	.8	.1	6	2.4	0.2	.1	2	.1	6	3	0

[1] Soluble sodium percent (SSP) = Na/total cations

[2] Data from Kelly (27)

Table 20.--Chemical composition of waters from piezometers at several locations and epths in the saline area

Location Sec., T., R.	Depth	Subsurface materials	Elect. cond.	B	Na	Ca+Mg	K	CO_3	Na	SAR
	Feet		*Mmhos/cm*	*P/m*	- - -	*Meq/l*	- - -	- - -	*Percent*	
9, 152 N., R. 51 W.	18	Lacustrine	30.0		257	213		0	55	25
9, 152 N., R. 51 W.	38	Lacustrine	11.5		69	71		T	49	20
9, 152 N., R. 51 W.	58	Lacustrine	9.5		75	42		0	63	16
19, 152 N., R. 51 W.	18	Lacustrine	3.0		19	13		0	59	8
19, 152 N., R. 51 W.	38	Till	4.2		34	13		0	72	13
19, 152 N., R. 51 W.	58	Sand	6.5		61	14		0	81	23
14, 152 N., R. 51 W.	18	Lacustrine	34.0		265	195		0	58	27
14, 152 N., R. 51 W.	38	Lacustrine	14.0		84	96		0	47	12
14, 152 N., R. 51 W.	58	Lacustrine	8.5		45	55		T	45	8
35, 152 N., R. 51 W.	58	Lacustrine	11.2	0.21	45	96	0.6		32	6
36, 151 N., R. 52 W.	65	Till	5.5		45	19		T	70	14
8, 151 N., R. 51 W.	58	Till	13.0		118	42		0	74	26
8, 151 N., R. 51 W.	58	Till	10.0	3.63	66	55	0.6		54	8

Table 21.--Chemical composition of shallow ground waters in shallow (12-foot deep) observation wells in the area. Wells are associated with specific soil profiles studied (see tables 14 and 15)

Soil profile	Location Sec., T., R.	Subsurface materials	Elect. cond.	B	Cations Ca	Mg	Na	K	Na	SAR	Anions CO_3	HCO_3	SO_4	Cl
			Mmhos/cm	*P/m*	- - -	*Meq/l*	- - -	- - -	*Percent*		- - -	*Meq/l*	- - -	- - -
--	16, 152 N., R. 50 W.	Lacustrine	4.3	0.02	24	34	6	-	9	1	0	6	57	3
5	9, 152 N., R. 51 W.	Lacustrine	58.3	.11	182	353	221	<1	29	14	0	3	38	722
12	36, 151 N., R. 52 W.	Glacial till	10.5	2.10	21	19	75	<1	65	17	0	7	41	69
9	33, 151 N., R. 51 W.	Lacustrine-Till	13.8	.40	24	116	58	<1	29	7	0	6	123	71
--	35, 152 N., R. 51 W.	Lacustrine	43.7	.10	71	228	253	nd	46	21	0	5	81	472
--	23, 151 N., R. 52 W.	Glacial till	20.0	.44	122[1]		140	0.7	53	18	-	-	-	-
6	30, 152 N., R. 50 W.	Lacustrine (Ridge)	45.4	.01	32	319	293	nd	45	22	T	3	214	432
--	30, 152 N., R. 50 W.	Lacustrine (Depression)	1.2	.04	8	4	2	nd	12	1	T	3	6	2
--	26, 153 N., R. 53. W.	Lacustrine	8.5	.11	27	90	16		12	2	0	7	98	31
8	8, 151 N., 51 W.	Lacustrine (Ridge)	29.9	.13	28	305	144		30	11	0	7	275	202
13	9, 151 N., 52 W.	Lacustrine-Till	16.8	2.30	36	34	114	<1	62	19	0	4	37	146
10	8, 150 N., 51 W.	Lacustrine	7.7	.40	24	75	17	<1	14	2	0	7	87	25
14	28, 151 N., 52 W.	Till (Sandy)	3.1	.20	23	16	3	<1	8	1	0	6	32	5

[1] Ca plus Mg.

Table 22.--Chemical composition of waters from shallow, 15-foot deep, observation holes in the saline area

Location Sec., T., R.	Soil materials	Elect. cond.	B	Ca+Mg	Na	K	Na	SAR
		Mmhos/cm	*P/m*	- - - -	*Meq/l*	- - -	*Percent*	
14, 152 N., 51 W.	Lacustrine	36.6	T	336	164	0.4	33	13
28, 152 N., 51 W.	Lacustrine	6.6	0.07	63	15	.2	19	3
16, 151 N., 52 W.	Glacial till	3.5	.17	32	6	.3	16	2
8, 151 N., 52 W.	Glacial till	5.6	1.23	32	32	.4	50	8
24, 151 N., 52 W.	Glacial till	20.0	.40	186	76	.7	25	8
35, 152 N., 51 W.	Lacustrine	36.0	.18	300	200	.8	40	16
9, 151 N., 52 W.	Glacial till	32.0	1.88	216	224	.7	51	22
23, 151 N., 52 W.	Glacial till	20.0	.44	122	140	.7	59	18
3, 152 N., 53 W.	Lacustrine-Till	11.6		60	80		57	15
36, 153 N., 53 W.	Lacustrine-Till	20.8		154	96		36	15
19, 153 N., 52 W.	Lacustrine	28.0		260	120		32	10
18, 153 N., 52 W.	Lacustrine	24.0		135	185		58	22
4, 153 N., 52 W.	Lacustrine	30.8		330	90		21	7
3, 153 N., 52 W.	Lacustrine	20.8		174	96		36	10
25, 154 W., 52 W.	Lacustrine	10.0		90	30		25	5
25, 154 W., 52 W.	Lacustrine	36.8		375	125		25	9
17, 154 W., 51 W.	Lacustrine	28.4		285	105		27	9

Table 23.--Average ground water salinity (as electrical conductivity), sodium content and water table depths in the saline area of Grand Forks County on two dates in 1962; and spring and fall ground water salinity in 1958

Sample source	Spring sampling: March 1962					Summer sampling: July 1962				
	Number sampled	Water table depth	Elect. cond.	Na	No. of Na analyses	Number sampled	Water table depth	Elect. cond.	Na	No. of Na analyses
		Feet	*Mmhos/cm*	*Meq/l*			*Feet*	*Mmhos/cm*	*Meq/l*	
Shallow wells:										
< 15 feet	41	9.7	14.9	68	23	41	4.6	14.2	72	23
20-foot piezometers	42	8.4	6.2	42	15	42	5.1	8.1	38	15
40-foot piezometers	5	8.2	5.8	37	5	5	5.9	5.8	42	4
60-foot piezometers	5	6.1	4.3	29	4	5	8.9	4.8	23	4
	Spring sampling: May-June 1958					Fall sampling: October 1958				
Shallow observation wells	57	4.6	15.7			61	7.4	13.5		

Table 24.--Comparison of salinity of shallow ground water in the spring and fall 1960, from 12-foot observation wells and 20-foot piezometers on ridges and in depressions located at N½ 8, T.151 N., R.51 W.

	Installations on ridges				Installations in depressions			
	Observation wells		Piezometers		Observation wells		Piezometers	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	- - - - - - - -	*Mmhos/cm*	- - - - - - - -		- - - - - - - -	*Mmhos/cm*	- - - - - - -	
	20.0	23.6	16.5	14.5	2.7	5.5	3.1	2.8
	17.8	20.0	6.2	6.3	1.9	2.5	2.6	2.3
	14.4	12.9	15.0	14.0	4.0	4.5	7.0	9.2
	9.8	9.5	8.3	8.0	0.6	2.0	1.4	2.0
	28.0	32.0	22.0	24.4	1.6	1.5	1.6	1.2
	18.0	18.4	13.0	14.0	0.6	1.7	1.4	1.2
	20.0	20.2	9.2	9.0	1.2	2.0	6.9	5.0
	11.6	20.0	16.5	12.8	0.9	1.8	7.8	8.0
	16.6	17.2	10.8	10.8	7.2	7.0	2.6	2.8
	9.5	8.6	7.2	7.0	5.2	6.5	5.0	6.1
	16.4	14.5	9.5	9.0	1.1	1.1	3.8	4.2
	22.2	13.0	9.8	9.6				
	13.8	13.0	9.5	12.3				
	24.5	24.0	9.5	9.4				
Average	17.3	17.3	11.7	11.5	2.5	3.3	3.7	4.1

Table 25.--A comparison of ground water salinity from three observation well depths under fallow (bare soil) and straw mulch during 2 years at SW¼ 11, T. 152 N., R. 51 W.

Sampling date	Average water table: Bare	Average water table: Mulch	Average electrical conductivity: 12-ft wells: Bare	12-ft wells: Mulch	9-ft wells: Bare	9-ft wells: Mulch	7-ft wells: Bare	7-ft wells: Mulch
	- - Feet - -		- - - - - - - Mmhos/cm - - - - - - -					
Nov. 15, 1961	5.9	5.8	11.0	19.5	nd 1/	nd	15.0	37.0
Jan. 3, 1962	9.9	8.7	11.7	17.3	nd	17.5	nd	nd
May 25, 1962	3.6	10.7	45.7	41.5	47.3	41.7	44.3	40.7
Jun. 13, 1962	4.2	1.3	46.7	44.0	46.0	44.0	45.1	44.0
Mar. 1, 1963	11.7	10.0	29.9	28.9	29.7	29.1	19.4	29.4
Jul. 29, 1963	4.1	4.0	40.5	16.1	30.5	17.1	10.1	17.1
Nov. 13, 1963	7.6	7.1	30.0	16.9	17.1	17.1	nd	nd

1/ Not determined.

Table 26.--Shallow ground water salinity at three depths under grass during 2 years at NE¼ 9, T. 151 N., R. 52 W.

Sampling date	Water table depth	Average electrical conductivity: 11-ft wells	9-ft wells	7-ft wells
	- -Feet- -	- - - - - - - - -Mmhos/cm - - - - - - - -		
Nov. 15, 1961	2.0	34.3	nd 1/	nd
Jan. 3, 1962	4.2	33.0	34.0	34.0
Mar. 15, 1962	9.1	35.7	nd	nd
Apr. 25, 1962	2.3	41.7	nd	nd
May 10, 1962	1.0	42.7	44.0	44.0
Jun. 20, 1962	2.0	39.9	44.0	44.0
Mar. 1, 1963	9.1	23.7	nd	nd
Jul. 29, 1963	4.4	36.0	36.5	37.2

1/ Not determined.

Table 27.--Chemical composition of surface streams in east and central Grand Forks County and adjacent areas on three dates (fig. 6, sampling locations)

Location	pH	Elect. cond.	Total cations	Na	K	Ca+Mg	B	Na	SAR
		Mmhos/cm	- - - - - - -Meq/l		- - - - - - -		P/m	Percent	
			November 13, 1958						
1	8.1	0.8	8.0	2.7	nd	5.3	nd 1/	34	2
2	8.2	3.0	29.5	20.0	nd	9.4	nd	68	9
6	8.1	8.5	105	81.1	nd	23.8	nd	77	24
7	8.5	.7	7.0	3.8	nd	3.2	nd	55	3
8	7.4	.7	7.2	4.5	nd	2.6	nd	63	4
10	7.9	7.9	94	71.7	nd	22.3	nd	76	22
11	7.8	1.0	9.9	6.2	nd	3.7	nd	63	5
12	7.9	.6	6.5	3.8	nd	2.6	nd	59	3
			June 4, 1959						
1	8.0	0.8	8.2	1.0	nd	72	nd	13	1
2	7.7	20.8	275	185	nd	90	nd	67	28
3	8.0	6.5	85	50	nd	35	nd	59	12
4	7.9	1.8	18	7.4	nd	10.6	nd	41	3
5	7.8	8.3	100	66	nd	34	nd	66	16
6	8.1	3.5	39	19	nd	20	nd	47	6
7	8.3	.6	6.0	1.0	nd	5.0	nd	17	1
8	8.0	.6	5.8	.8	nd	4.8	nd	14	1
9	7.7	14.4	180	100	nd	80	nd	56	16
10	7.8	7.0	82	46	nd	36	nd	56	10
11	8.0	.8	7.5	1.0	nd	6.5	nd	13	1
12	7.6	.6	6.0	.8	nd	5.0	nd	13	1
			October 27, 1959						
1	7.4	0.7	7	0.7	0.2	6	0.14	10	1
2	7.8	12.0	150	120	2.0	30	nd	80	31
3	7.9	9.6	116	69	1.3	47	nd	59	12
4	7.9	4.5	50	30	.5	20	nd	60	9
5	8.0	12.8	160	94	2.0	66	3.60	59	16
6	8.0	12.0	150	72	1.6	78	nd	48	12
7	8.4	.6	6.5	.8	.1	6	nd	12	1
9	8.1	13.2	165	98	1.9	67	3.60	59	17
10	8.0	12.4	154	68	1.5	86	2.60	44	10
11	7.8	.4	4.5	1.2	.1	3	nd	27	1
12	7.6	.6	5.5	.6	.1	5	nd	11	1

1/ Not determined.

Table 28.--A comparison of actual soil water contents, average soil electrical conductivity and unavailable soil water because of salinity in a saline ridge and adjacent relatively nonsaline depression at N½ 8, T. 151 N., R. 51 W. Area cropped to barley

Soil depth	Two depressions: Average water content	Average electrical conductivity	Average unavailable soil water 1/	Two ridges: Average water content	Average electrical conductivity	Average unavailable soil water 1/
Inches	Percent wt	Mmhos/cm	Percent	Percent wt	Mmhos/cm	Percent
6-18	15.8 2/	1	< 2	31.0	9	32
30-42	24.1	< 2	< 5	28.7	15	75
54-66	31.9	2	< 5	37.5	13	50

1/ Percent of soil water between 0.3 and 15 atmospheres tension unavailable due to soil salinity.

2/ Percent by weight x 1.3 = percent by volume.

Table 29.--A comparison of average soil water stress (negative hydraulic head) under grass and fallow at SW¼ 34, T. 152 N., R. 51 W.

Treatment	Soil depth - inches: 4	8	12	16	20	36
	- - - - - - - - - - -Millibars- - - - - - - - - -					
Fallow	306	270	180	162	151	-
Grass	> 800	> 800	> 800	444	420	411

Table 30.--Surface (0 to 6 inches) soil salinity,[1] water-table depths, and precipitation on native grass sites

Location:	NW 35 Rye		SW 14 Rye		NW 21 Blooming		SE 15 Oakville		NW 11 Blooming		NW 7 Falconer		SE 3 Brenna		Precipitation between periods
Date	EC	Water table	EC	Water table	EC	Water table	EC	Water table	EC	Water table	EC	Water table	EC	Water table	
	Mmhos	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Inch*
Apr. 10, 1958	5.6	4.2	8.6	2.5	8.0	5.9	7.2	4.7	5.3	6.4	3.7	7.4	3.3	7.7	0.66
May 13	9.6	2.8	18.8	4.7	-	2.9	-	2.3	-	4.4	-	3.7	-	5.4	2.44
Jun. 9	6.0	1.4	22.4	4.1	11.6	1.9	8.2	2.7	4.7	3.2	5.6	3.3	3.6	4.9	5.30
Jul. 11	5.0	2.3	19.2	0.1	-	1.8	6.0	1.7	5.2	2.6	4.4	2.1	1.0	3.9	1.88
Aug. 7	11.0	2.5	16.4	4.5	9.6	5.2	11.6	4.6	7.2	5.2	-	5.6	1.6	6.1	1.61
Sep. 10	13.2	4.3	26.4	6.5	12.4	6.6	-	6.7	8.7	6.9	-	7.9	2.5	7.6	1.33
Oct. 15	15.6	5.4	38.4	7.0	10.8	7.4	13.4	7.8	11.0	7.6	-	8.6	2.2	8.3	0.40
Nov. 12	16.8	5.7	36.0	7.7	11.0	7.4	15.0	8.0	10.8	7.9	-	8.8	2.7	8.5	
Average	10.3	3.6	23.3	4.6	10.6	5.7	10.2	4.9	7.6	5.7	4.8	4.3	2.4	6.7	
Total precipitation from November 12, 1958 to April 6, 1959:															4.52
Apr. 6, 1959	-	0.7	3.3	2.0	10.2	4.0	-	1.7	11.6	4.5	6.0	4.6	2.2	5.0	1.05
May 11	13.2	1.4	8.8	3.0	10.6	4.7	6.4	2.3	12.0	4.6	8.0	2.8	1.3	4.9	3.57
Jun. 15	4.5	2.4	9.8	4.6	8.8	4.3	9.2	2.9	11.8	4.8	10.0	4.4	2.0	4.6	3.32
Jul. 15	17.6	2.2	11.0	3.1	9.4	4.2	10.0	3.9	9.0	4.7	6.7	3.8	3.1	6.1	2.03
Aug. 17	12.9	6.1	12.8	5.4	8.2	6.5	14.6	6.6	14.0	6.2	9.4	7.2	3.6	7.4	1.04
Sep. 15	13.5	7.4	18.8	6.5	10.6	7.3	12.0	7.7	12.2	7.0	6.9	8.0	4.8	8.1	2.70
Oct. 13	12.0	4.1	11.0	3.0	6.7	5.7	7.6	6.1	5.8	6.4	6.8	8.6	2.5	8.2	
Average	12.3	3.9	10.8	3.9	9.2	5.2	10.0	4.9	10.9	5.5	7.7	5.6	2.8	6.3	
Total precipitation from October 13, 1959 to May 9, 1960:															6.14
May 9, 1960	4.2	1.1	5.9	2.1	5.1	4.4	2.2	1.6	4.9	3.9	3.7	1.9	3.0	3.9	2.66
Jun. 20	5.5	2.3	8.0	4.1	7.2	4.0	6.5	3.1	6.8	5.0	7.0	3.7	2.6	5.0	4.19
Jul. 18	6.0	1.9	5.4	3.2	9.0	5.5	8.4	4.6	6.1	5.6	8.7	5.5	2.6	5.9	2.01
Aug. 15	15.0	4.5	9.1	5.8	8.8	7.0	11.2	6.2	8.4	6.7	8.2	7.8	3.7	7.4	2.70
Sep. 27	24.4	6.1	23.4	6.7	18.2	7.4	19.6	6.6	19.2	7.7	18.5	8.8	-	8.1	
Average	11.0	3.2	10.4	4.4	9.7	5.7	9.6	4.4	9.1	5.8	9.2	5.5	3.0	6.1	

1/ Electrical conductivity (EC) of saturated soil extracts in millimhos per centimeter.

Table 31.--Surface (0 to 6 inches) soil salinity,[1] water table depths, and precipitation on cropped land

Location:	NW 33 Brenna		SE 29 G.F.		NE 8 Brenna		NW 19 Rye		NE 24 Brenna		NE 34 Blooming		NW 8 Falconer		
Crop cover:	Fallow, barley, barley		Sugar beets, barley, barley		Wheat barley, fallow		Fallow(S.C.), barley, barley		Potatoes, wheat, barley		N. grass, barley, flax		Wheat, oats, potatoes		Precipitation between periods
Date	EC	Water table	Ec	Water table	EC	Water table	EC	Water table	EC	Water table	EC	Water table	EC	Water table	
	Mmhos	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Mmhos*	*Ft*	*Inch*
Apr. 10, 1958	-	-	-	-	-	7.8	3.5	8.1	3.5	8.1	1.3	7.0	1.0	9.4	0.66
May 13	-	-	-	5.9	17.6	4.8	4.2	5.2	-	7.7	-	3.9	-	9.3	2.44
Jun. 9	-	-	-	5.7	10.2	4.7	3.7	4.3	4.2	7.1	-	4.8	1.3	5.9	5.30
Jul. 11	-	-	5.2	4.8	7.3	4.6	3.1	3.5	1.5	2.5	1.4	4.6	2.3	5.9	1.88
Aug. 7	-	-	6.8	7.5	9.5	6.8	3.5	4.8	3.1	5.3	1.0	6.7	1.6	7.6	1.61
Sep. 10	-	-	6.3	8.9	12.8	8.2	4.8	5.7	2.9	7.1	-	8.1	2.1	8.5	1.33
Oct. 15	8.6	5.3	7.0	9.6	13.6	9.0	5.5	6.4	3.4	8.0	4.2	8.8	3.1	9.2	0.40
Nov. 12	8.4	5.6	6.2	9.9	17.6	9.5	6.0	6.7	3.2	8.2	3.8	8.2	3.1	9.7	
Average	8.5	5.4	6.3	8.2	12.7	6.8	4.3	5.6	3.1	6.6	2.3	7.1	2.1	8.0	
Total precipitation from November 12, 1958 to April 6, 1959:															4.52
Apr. 6, 1959	6.5	5.2	6.6	7.2	8.0	1.7	5.6	6.1	3.7	3.1	1.3	5.2	2.0	10.1	1.05
May 12	10.0	4.6	8.0	6.6	8.9	3.9	5.8	7.3	5.1	4.4	3.8	5.5	3.8	9.0	3.57
Jun. 16	7.1	3.4	6.5	5.9	5.6	4.8	4.9	6.7	2.9	4.0	1.4	5.8	1.2	7.6	3.32
Jul. 16	5.6	4.9	6.7	7.4	9.0	6.6	6.0	7.6	3.8	5.8	2.8	7.4	1.6	8.0	2.03
Aug. 18	9.2	5.8	9.2	8.1	15.0	7.9	5.6	7.9	4.0	7.3	5.0	9.4	.6	8.3	1.04
Sep. 16	7.0	6.4	8.8	8.5	12.0	8.9	7.0	8.5	3.8	8.0	4.6	10.7	.9	10.3	2.70
Oct. 12	7.1	6.3	6.2	8.9	9.2	9.6	4.7	8.6	2.8	7.6	1.3	11.4	.5	10.9	
Average	7.5	5.2	7.4	7.5	9.7	6.2	5.7	7.5	3.7	5.7	2.9	7.9	1.5	9.2	
Total precipitation from October 12, 1959 to May 9, 1960:															6.14
May 9, 1960	6.0	4.9	6.0	5.4	-	6.5	4.7	6.2	4.3	-	0.7	3.6	0.2	6.8	2.66
Jun. 20	-	4.8	-	6.3	-	5.7	-	7.0	4.2	5.9	2.6	5.7	.2	6.4	4.19
Jul. 18	7.6	6.0	6.0	7.4	4.9	6.0	2.2	7.4	3.4	6.4	3.9	6.7	.4	7.0	2.01
Aug. 15	8.6	6.6	8.2	8.4	5.6	6.7	4.5	8.1	3.4	7.6	5.6	8.6	1.4	6.4	2.70
Sep. 27	10.3	6.8	15.7	9.1	11.0	6.8	8.8	8.7	9.7	8.7	10.4	10.5	.9	9.2	
Average	8.1	5.8	9.0	7.3	7.2	6.3	5.1	7.5	5.0	7.2	4.6	7.0	.6	7.2	

1/ Electrical conductivity (EC) of saturated soil extracts in mmhos per centimeter.

GPO 812-374-2